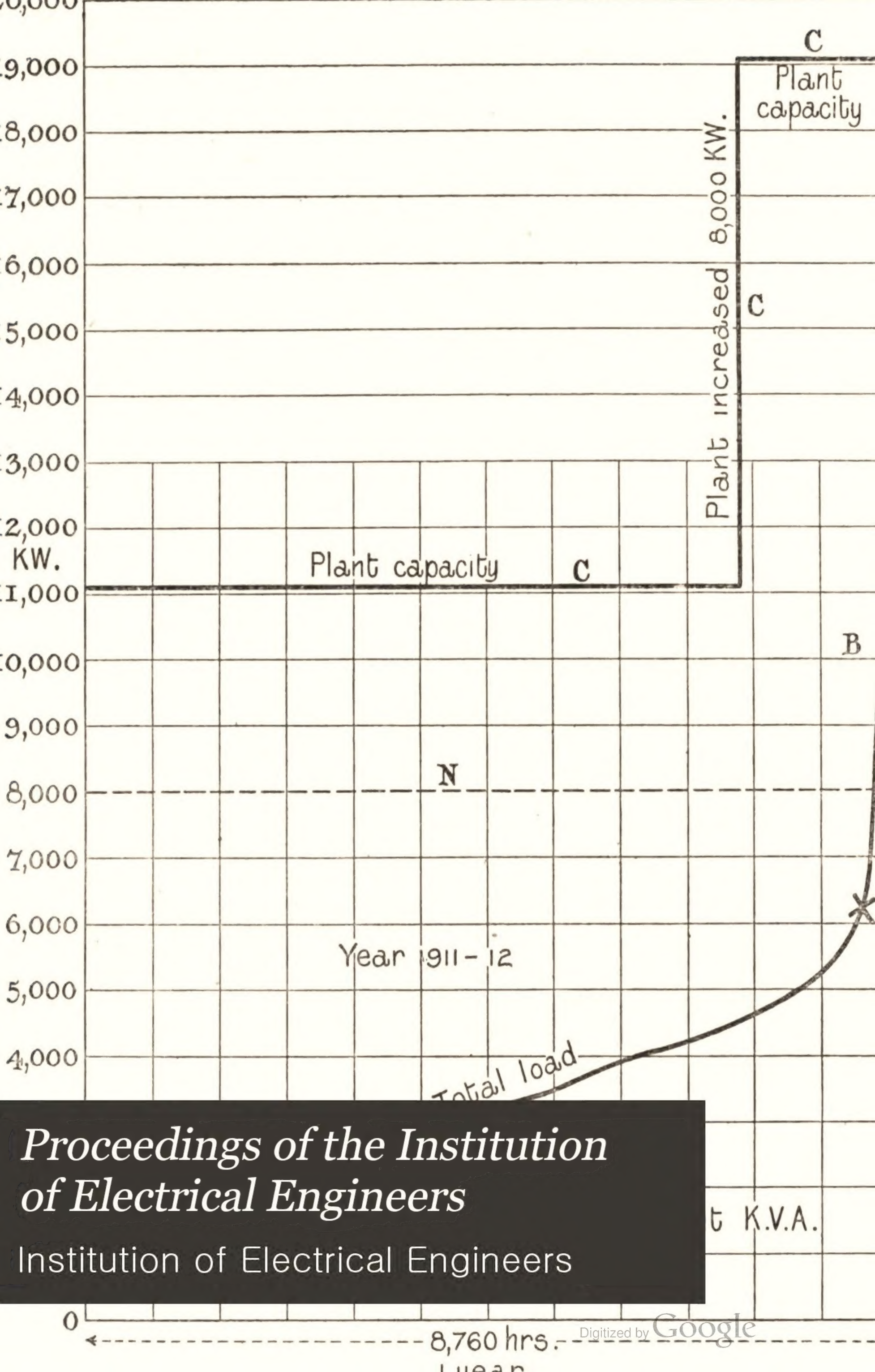
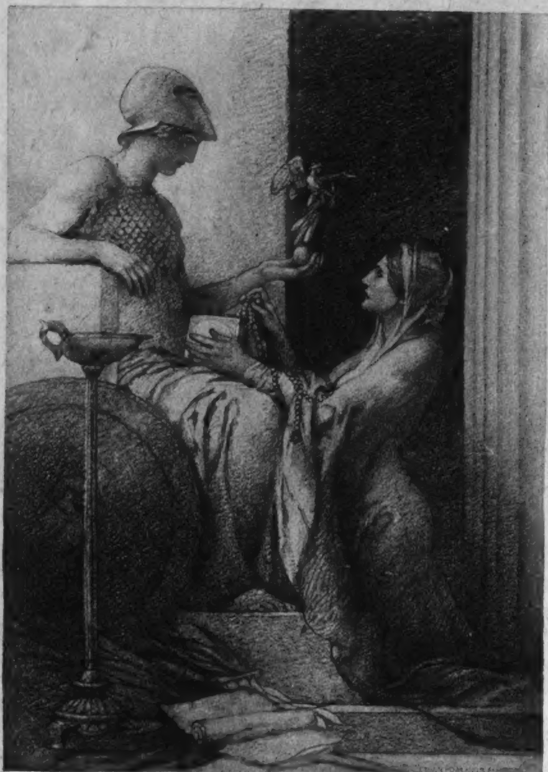


Proceedings of the Institution of Electrical Engineers

Institution of Electrical Engineers



JOURNAL

OF THE

INSTITUTION OF ELECTRICAL ENGINEERS,

ORIGINALLY

THE SOCIETY OF TELEGRAPH ENGINEERS.

FOUNDED 1871. INCORPORATED 1883.

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1912.

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VOL. 49, 1912.

JOURNAL

OF

The Institution of Electrical Engineers.

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VOL. 49. 1912. No. 214.

Proceedings of the Five Hundred and Thirty-third Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, 8th February, 1912—Mr. S. Z. DE FERRANTI, President, in the chair.

The Minutes of the Ordinary General Meeting, held on 25th January, 1912, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

John Purrett. | Edward Rayner.

From the class of Associates to that of Members :—

Baron F. W. de Tuyll. | Frederick A. Nixon.

From the class of Associates to that of Associate Members :—

Frank J. Hawkins. | Arthur Taylor.

From the class of Students to that of Associate Members :—

Douglas W. Belbin.
Arthur L. Coward.
Harry R. Greenyer.
William H. Grinsted.
Andrew Henderson.
Arthur R. Hinde.
Henry Thos. Jager.
Alexander Kinnes.
Cecil Reid McGowan.
Frank A. McGowan.
John J. McKenna.
Charles Mark-Seymour.
Ernest Morgan.
John H. Mousley.
James Parkinson.
Thomas Y. Porter.
Henry William Powell.
Francis E. Robinson.
Rupert A. Sharpe.
Robert Shaw.
John William Smith.
Edwin James Stiell.
Albert E. Uffellmann.
Alex H. St. C. Watson.
Robert Yorke.
Arthur P. Young.

From the class of Students to that of Associates :—

Charles Alexander Pilson.

The PRESIDENT ; I have to announce to you that last year the Council decided that, if possible, meetings of the Institution should be held in the districts of the different Local Sections, part of the time being given to visiting the industries of the particular district. Following out that policy, the Council have decided this year to hold a summer meeting at Glasgow, which will commence on the 12th June and end on the 14th June. There will be various papers read, according to arrangements made with the Local Section, and certain works of interest in that part of the country will be visited by the members participating in this meeting. It is thought these meetings will bring the Council and the members of the Institution into closer touch with one another, and help to keep interest in the doings of the Institution alive in the different parts of the country. I am therefore pleased to be able to announce that the first of these summer meetings will take place in Glasgow on the dates that I have named. I have also to announce to you that Mr. C. E. Spagnoletti, Past President, has been elected an Honorary Member of the Institution. I need hardly say anything to you about Mr. Spagnoletti, but I would like to remind the younger members present that very many years ago he did great and useful work in the development of telegraphy. Nowadays many of us are apt to think lightly of electrical work which has not a big electrical power at its back, but I would remind you that work of the very greatest importance was done many years ago in the first commercial application of electricity, namely, the telegraph ; and I am pleased that we should be able to elect to-day as one of our Honorary Members so distinguished an inventor and worker in the development of the telegraph system as Mr. Spagnoletti.

A paper by Mr. E. H. Rayner, Member (from the National Physical Laboratory), entitled "High-Voltage Tests and Energy Losses in Insulating Materials" (see page 3), was read and discussed.

HIGH-VOLTAGE TESTS AND ENERGY LOSSES IN INSULATING MATERIALS.

By E. H. RAYNER, M.A., Member.
(FROM THE NATIONAL PHYSICAL LABORATORY.)

(*Paper first received* 31st *August*, 1911, *received in final form* 24*th April*, 1912, *and read before* THE INSTITUTION 8*th February*, 1912.)

PREVIOUS WORK.

In a previous paper * the author has described the results of an earlier research on insulating materials. In the first part of the paper experiments were described which were especially directed to the investigation of the effect of temperature on insulating materials with a view to determining the temperature above which definite mechanical and electrical deterioration took place. This was done by subjecting insulating materials to different temperatures for various intervals of time and noting the resulting change in electric strength. The change in mechanical properties was determined by measuring the force required to punch a hole a quarter of an inch in diameter through the material, and also by bending the material round cylinders of different diameters, observing the curvature necessary to crack it. The results in general were that while the electric strength was usually increased by treatment to temperatures up to 125° C. for several weeks, the decrease in desirable mechanical properties was often very marked, and a temperature of 100° C. seemed to be higher than desirable.

The second part of the paper dealt with the temperature of field coils of dynamos and motors. By embedding thermo-junctions at various depths in the coil the temperature curve inside it could be plotted and the highest temperature reached accurately estimated. This was naturally higher than the average temperature rise calculated from the increase in resistance of the field coil itself. As the result of tests on a number of machines under ordinary working conditions, it was found that the maximum internal temperature might be expected to reach 20° C. higher than the average—as measured by increase in resistance of the field winding. Other experiments were done in a similar manner, measuring by thermo-junction the internal temperatures of alternating and continuous-current armatures, comparing them with surface temperatures as measured by mercury thermometers. As was

* "Report on Temperature Experiments carried out at the National Physical Laboratory," *Journal of the Institution of Electrical Engineers*, vol. 34, p. 613, 1905.

expected, the difference was never found to be nearly so large, and it is quite negligible.

Another series of experiments was done on transformers. Most of these were oil-cooled, of 20-k.w. capacity, 50 cycles, 2,000–100 volts. Thermo-junctions were inserted in various places in both windings and their temperatures measured, while full load was maintained on the transformers. When steady temperature conditions had been attained, a matter of some 20 hours under a steady load, the final readings indicated that the highest temperature might exceed the mean, as measured by increase in resistance of the windings, by about 15° C. The copper losses in the transformer in this case would be about 400 watts. These figures correspond to a test in which the highest temperature reached was 80° C., and the air temperature was 20°. The thermometers in the oil indicated 55° C. at the top and 35° at the bottom.

Object of Research.

The present paper describes experiments which have been made during the last three years on some insulating materials which are commonly used in electrical apparatus working at a high voltage. The work has been carried out at the request of the Engineering Standards Committee. The author acknowledges his grateful appreciation of their permission to publish the results in this paper.

Having before them the consideration of pressure tests for electrical plant working at a high voltage, the Sub-Committee on Generators, Motors and Transformers requested the National Physical Laboratory to investigate the results of the application of a high voltage to insulating materials. The point on which information was specially requested was whether damage to insulation of electrical plant was more likely to be caused by a short application of a high-test voltage, or by a longer application of a lower voltage.

The materials commonly used for the insulation of high-voltage plant are varnished and oiled cloths and papers and preparations of mica. A considerable amount of work has been done on mica, which is described later; but more attention has been devoted to the physical effects of high electrostatic stress on the more complex organic materials, chiefly oiled and varnished cloth and paper. Various qualities of these materials were placed at the disposal of the Laboratory by the British Westinghouse Company, the Micanite and Insulators Company, and by Messrs. Meirowsky, of Cologne, and much of the work has been done on these materials.

As will be seen from the experiments to be described later, a research of this nature labours under the great disadvantage that, unlike the ordinary mechanical testing of the materials, the results depend very largely on such physical conditions as temperature and humidity. These important external influences, and, very commonly, the great variation of a large number of successive similar experiments from their mean, often largely mask the effect looked for, which may be, for

instance, the result of a short application of a high voltage on the general qualities of a material. This naturally greatly increases the time taken, and a whole series of experiments may give no trustworthy result from these causes.

The general aim of the research has been to attempt to discover the effect on the electric strength of the materials of the application for some time of a voltage which may be—perhaps, 30 per cent. to 90 per cent. of that which will produce breakdown in a few seconds. The second part of the paper goes further into the physics of electric strain, and deals with the results obtained from measurements of the energy absorbed when insulating materials are subjected to alternating stress.

During the research the result of one experiment continually suggested modifications in conditions and apparatus for the next. The conclusions arrived at will, in many cases, be most easily followed by quoting the results of some typical experiments in detail, indicating their bearing on the result of previous and following ones.

Apparatus.

For the purpose of this research the Engineering Standards Committee presented to the laboratory the necessary generating plant. This consists of a 20-k.w., 200-volt, 40 to 60 cycle motor alternator with field resistances, and a transformer of 100,000 volts with both high- and low-tension winding divided into halves. There is also a subsidiary auto-transformer by which, for comparatively low voltages, the 200-volt winding of the high-tension transformer may be fed at $\frac{1}{20}$, $\frac{1}{10}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{1}{1}$ of the voltage generated by the alternator. The generator was designed to give a very smooth voltage curve. These were constructed by the British Westinghouse Company. For the accurate measurement of high voltages the Laboratory has added an electromagnetic precision voltmeter of 500 volts, together with resistances amounting in all to 99·5 times that of the instrument (Fig. 1). By this means 100,000 volts can be measured; and, by switches which can be operated while the circuit is alive, sections of the resistances can be short-circuited so that full reading (1,000 scale divisions) may be obtained with 500, 1,000, 2,000, 5,000, 10,000, 20,000, 40,000, and 100,000 volts. At 100,000 volts 2 k.w. is absorbed in the resistances, which amount to 5 megohms.

The voltmeter and its resistances were made by Hartmann and Braun, while the switchgear and the mounting for the whole apparatus were made at the Laboratory.

A diagram of the connections is given in Fig. 1, in which the voltmeter switches are shown as arranged for use with all the resistances in circuit.

A large electrically heated oven has been constructed for doing experiments at any temperature up to 200° C. The high-voltage conductors pass through porcelain tubes in the oven wall. An electric fan is employed to circulate the air inside the oven, and the temperature is regulated by a thermostat.

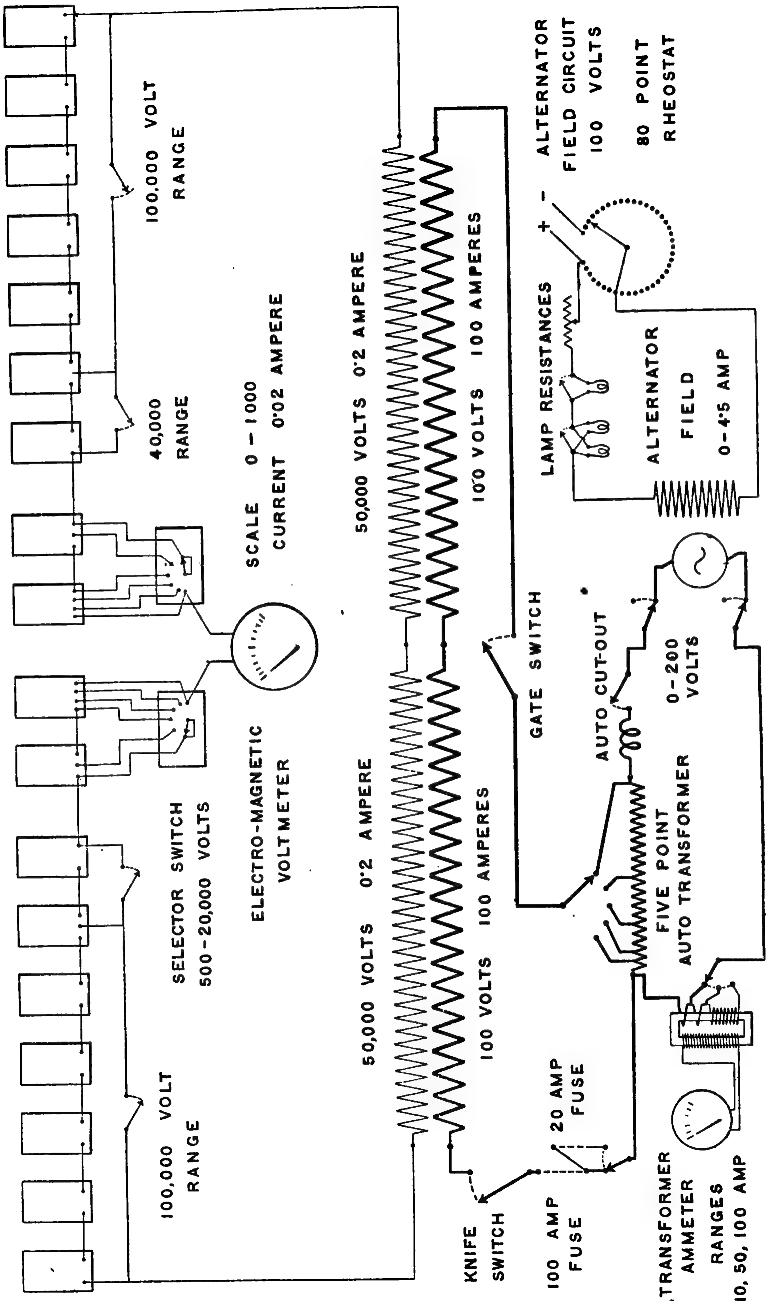
100,000 VOLT RANGE
40,000 RANGE
SCALE 0 – 1000
CURRENT 0·02 AMPERE
50,000 VOLTS 0·2 AMPERE
100 VOLTS 100 AMPERES
ALTERNATOR FIELD CIRCUIT 100 VOLTS
80 POINT RHEOSTAT
+
-
LAMP RESISTANCES
ALTERNATOR FIELD 0-4·5 AMP
GATE SWITCH
AUTO CUT-OUT
0-200 VOLTS
FIVE POINT AUTO TRANSFORMER
SELECTOR SWITCH 500-20,000 VOLTS
ELECTRO-MAGNETIC VOLTMETER
50,000 VOLTS 0·2 AMPERE
100 VOLTS 100 AMPERES
100,000 VOLT RANGE
20 AMP FUSE
KNIFE SWITCH
100 AMP FUSE
TRANSFORMER AMMETER RANGES 10, 50, 100 AMP

FIG. 1.

For the experiments described in the latter portion of the paper a high-voltage electrostatic wattmeter with the necessary resistances and switches was constructed. This has been used for power measurements up to about 15,000 volts. Unless otherwise stated, a frequency of 50 cycles per second has been used. Temperatures are in °C.

Electrodes.

For the application of the voltage to oiled fabrics, etc., brass electrodes were used. In accordance with a suggestion in a paper on this subject by C. E. Skinner,* they were made with well-rounded edges, the radius of curvature being 1½ in. (Fig. 2, No. 1). These were replaced later by others of sharper curvature at the edge, as it was found that the increased voltage stress was more than compensated by the weakness caused by the heating due to increased brush discharge

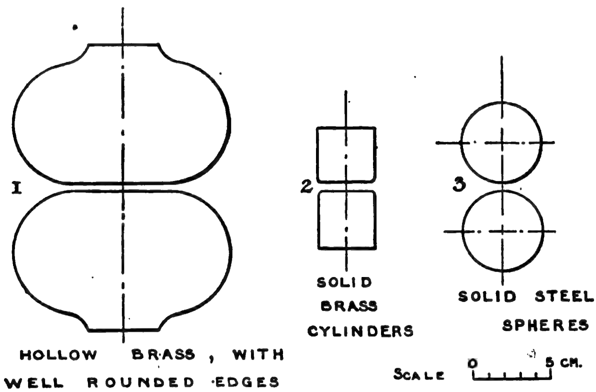

FIG. 2.—Electrodes.

when edges of large radius of curvature were used (No. 2). The effective surface of these electrodes was a circle of 38 mm. (1·5 in.) diameter, the edge being rounded to a radius of about 3 mm. (⅛ in.). For the experiments on mica steel spheres 5 cm. (2 in.) in diameter were employed (No. 3).

Effect of Number of Layers of Insulation.

One of the first tests on the materials was to find how electric stress at breakdown varies with the number of sheets used. These materials are always used in several layers in high-voltage machinery, and these experiments gave information as to the number of layers which might be considered most suitable for further testing of the material.

Table A gives the results of a series of tests of breakdown using from one to ten layers of thin oiled paper.

* *Transactions of the American Institute of Electrical Engineers*, vol. 19, p. 1047, 1902.

The voltage was in each case raised to the value given in Table A, so that breakdown occurred in about 20 to 40 seconds. It will be noted that when several thicknesses are tested the voltage per sheet falls as the number of sheets is increased. When only two

TABLE A.

Thin Oiled Paper, 0·095 *mm.*

Sheets.	Voltage per Sheet.
1	1,080
2	1,995
3	2,300
4	2,210
5	1,920
7	1,770
8	1,800
10	1,770

or three layers are tested the voltage per sheet rises. This is due to the thinness of the sheets, as the weakest parts of a sheet are generally much weaker than the average when the sheets are of so thin a material as this. On putting two or three thicknesses together, the weak spots in one sheet are generally covered by stronger parts of the others. The following list of observations from which some of the above figures are obtained show this effect, and also show the increased concordance of the results when several layers are tested at once.

TABLE B.

Thin Oiled Paper, 0·095 *mm.*

	Breakdown Voltage. One Sheet.	Breakdown Voltage. Four Sheets.
	800	9,600
	1,080	7,200
	800	8,900
	1,180	9,000
	1,420	9,300
	1,020	9,100
	720	——
	980	8,850
	1,360	
	1,440	
Average volts per sheet	1,080	2,210

The results on somewhat thicker oiled materials show a fall in voltage per layer when more than about two layers are tested together. For still thicker materials the voltage per layer falls from the first owing to the decreased proportional effect of small local variations in

the thickness and quality of the material, and to the less efficient cooling of the metal electrodes (Table C).

The thin varnished paper 0·095 (Table A) was tested as follows: Four thicknesses were taken, and as the mean of about eight tests the average breakdown voltage was found to be 8,230 volts, when the pressure was raised to the breakdown point in about 20 seconds. Other portions of the sheet were then subjected to half this voltage for a quarter of an hour, and then the voltage was raised till puncture took place.

Another sheet was then taken and its normal breakdown voltage found in the same way, and other portions were treated to one-half of the average of these figures for half an hour. Again, a third sheet was treated for one hour to half the voltage that would produce breakdown in about 20 seconds. It will be noted that the initial breakdown

TABLE C.

Number of Sheets.	Average Breakdown Voltage per Sheet.		
	Oiled Cloth, No. 5, 0·14 mm.	Oiled Cloth, No. 7, 0·18 mm.	Red Empire Paper, 0·17 mm.
1	3,600	5,780	4,720
2	3,750	4,020	4,110
3	3,250	3,410	3,370
4	—	3,065	3,070
5	—	2,920	—
6	—	2,770	—

voltages are not the same for the various sheets, as small differences of thicknesses in sheets of this size, 0·095 mm., make a considerable difference in the result, but the time test was made on portions of the same sheet used to ascertain the voltage which should be applied.

A series of similar tests was made by subjecting portions of the material to 4,000 volts for 5 minutes only, and then determining the breakdown voltage. This was found to average 9,180 volts. Alternate portions of the sheet were tested in a similar way, but without the previous application of the 4,000 volts. The average breakdown voltage was 9,140, showing that the short application does not produce any measurable depreciation. The results given in Table D, though the average of several determinations, show how uncertain tests of this kind always are—the depreciation after 1 hour coming out somewhat less than after half an hour. They do, however, indicate a

distinct lowering in electric strength. Each of these results is the average of about eight experiments, of which a single one would vary up to 5 per cent. from the mean.

TABLE D.

Four Thicknesses of Oiled Paper, 0·095 mm.

Breakdown Voltage in about 20 Seconds.	Voltage Applied.	Time of Application.	Resulting Breakdown Voltage.	Percentage Change.
		Minutes.		Per Cent.
8,230	4,115	15	7,580	8
7,900	3,950	30	6,780	14
8,760	4,380	60	7,820	11

A common method of working is to apply a high voltage and to observe how long the material will withstand this before being pierced. The following tests (Table E) on the same material show the kind of results obtained :—

TABLE E.

Thin Oiled Paper, 0·095 mm. (Four Thicknesses).		*Oiled Cloth, No. 5, 0·14 mm. (Three Thicknesses).*	
Voltage.	Time Elapsing before Failure.	Voltage.	Time Elapsing before Failure.
	Seconds.		Seconds.
15,000	0·0	10,000	3·7
12,500	0·5	9,000	10·3
11,000	1·2	8,000	14·6
10,000	4·6	7,000	78·0
9,000	14·0	6,500	617·0
8,000	105·0	—	—

Working on these lines, one method of determining whether a material has suffered by any treatment is to subject it to a voltage which will break it down, and to compare the time required with that required by similar material which has not been subjected to the treatment in question. It is of considerable importance to choose, by trial,

a suitable voltage for the purpose. It must not be so high as not to differentiate between the two satisfactorily, nor yet so low that several minutes are required, as then small differences in individual specimens and in their physical condition are found to make a very great difference in the time required to produce failure of the material. These differences are much less pronounced if the time of breakdown does not

TABLE F.

Varnished Cloth, No. 7 (Two Thicknesses).

	9,000 Volts.	8,000 Volts.	7,000 Volts.
	Seconds.	Seconds.	Seconds.
Time ...	2·8	13·0	5·5
" ...	3·8	7·8	117·0
" ...	3·5	8·0	37·0
" ...	3·4	10·0	230·0
Average ...	3·1	9·7	110·0

exceed about a minute. The above results (Table F) showing the time between application of the voltage and failure illustrate this point.

A series of tests were made on oiled cloth as follows: Three thicknesses were taken and were expected to have a breakdown voltage of about 8,000 volts when the voltage was raised to this value in 20 seconds. They were subjected to one-half of this voltage for half an hour and the breakdown voltage determined. Between each

TABLE G.

Oiled Cloth, No. 5 (Three Thicknesses).

	Breakdown Voltage.	Breakdown Voltage after Half an Hour at 4,000 Volts.
Dry day	8,900	8,500
Damp day...	8,000	7,200

experiment tests were made on adjacent portions of the materials which were not subjected to the treatment at 4,000 volts. It was discovered that very small temperature alterations would make considerable differences in the time of breakdown, and in order to get comparative results it is necessary to alternate experiments in this way to minimise the effect of changes of atmospheric temperature.

These experiments were repeated on another day, the one being fine and dry and the other wet. The results show how deceptive experiments done under different conditions may be.

To investigate further the effect of dampness a series of tests under similar conditions were made on three materials, the breakdown voltage being measured as follows :—

TABLE H.

	Air Desiccated with Calcium Chloride (1 Week).	Dry Day.	Damp Day.	Air Saturated with Moisture (1 Week).
Oiled cloth, No. 5 (three thicknesses)	11,160	8,300	7,150	5,850
Oiled cloth, No. 7 (two thicknesses)	10,800	9,000	7,550	6,400
Oiled paper (two thicknesses)	9,750	8,200	8,300	7,300

Such results as these made the consideration of the possibility or the desirability of attempting to work at a standard temperature and dampness of atmosphere a question of importance. Results of experiments which will be described later show that every degree of temperature often makes so much difference in the electrical qualities that a constant room temperature to be of any use was practically unattainable. For these later experiments a large electrically heated oven was built and maintained automatically at a constant temperature. They show how sensitive oiled and varnished materials are to small changes of temperature. The question of possible desiccation of the materials to reduce the variability caused by different degrees of humidity was of a similar nature. Whether done by a chemical desiccator or by heat, the material would be in an unknown condition after treatment, and this condition would be different for different materials, and would vary with the time to which it was subjected to such treatment.

Moreover, and this was the most important consideration, these materials, whatever drying they may have had in vacuum ovens as parts of armature coils, etc., have, by the time the machines have been erected, generally been in a damp atmosphere, very likely at a temperature below the dew point. They are, therefore, in a condition very different from that produced by artificial desiccation by heat or otherwise, and the results obtained from experiments on materials after artificial drying would have to be modified to a very uncertain extent in order to make them applicable to materials in a damper condition. Experiments were, therefore, generally done varying one condition at a time as far as possible, doing control experiments on similar material not subjected to the physical condition in question.

The great effect that temperature will often have on the time of breakdown of highly stressed insulation is shown in the following table of results of tests on oiled cloth at three temperatures.

TABLE J.

No. 12, Oiled Cloth (One Thickness).

Volts Applied.	Time of Breakdown.		
	Air Temperature. 11° C.	Air Temperature. 14° C.	Air Temperature. 18° C.
7,000	21·0 minutes	8·3 minutes	25·0 seconds
8,000	13·5 seconds	10·0 seconds	8·5 ,,

Quantitative experiments on the internal heating of insulation described later will give more insight into this effect.

As the application of a high voltage to these materials involves an appreciable waste of energy and consequent heating of the material and electrodes, an apparent weakening may result from this cause, if a breakdown voltage be applied before the material has cooled to atmospheric temperature. The following experiments illustrate this effect. Nine thousand volts, which would result in failure of the material in about 1½ or 2 minutes, was first applied for 1 minute. This was followed by an application of 11,000 volts, which alone would produce failure in about 12 seconds. An interval was allowed between the two of from 0 to 2 minutes. In a second experiment the interval was from 0 to 60 seconds.

TABLE K.

Oiled Cloth, No. 12 (Two Thicknesses, 9,000 Volts, applied for 1 Minute followed by 11,000 Volts).

Period of Rest.	Time of Application of 11,000 Volts.	Period of Rest.	Time of Application of 11,000 Volts.
0	2·6 seconds	0	2·5 seconds
1 minute	9·5 ,,	5 seconds	4·4 ,,
2 minutes	11·9 ,,	15 ,,	9·0 ,,
Fresh material	12·0 ,,	60 ,,	9·8 ,,
—	—	Fresh material	10·5 ,,

In this connection may be mentioned some tests on one thickness of the same material which was subjected to electric stress for a much longer time, some specimens for a period of one hour and some for two.

The voltage applied was 5,000, and the materials and electrodes were left all night to cool. Next morning they were tested at 6,500 volts with the following result :—

TABLE L.

Time of Treatment at 5,000 Volts.	Time of Breakdown at 6,500 Volts.
1 hour	6·5 minutes
2 hours	3·0 seconds
Fresh material	22·0 minutes

This shows how serious the effect of a long time test may be. Other experiments on these lines gave similar results. After similar treatment at 5,000 volts for one hour 7,000 volts caused failure in one-sixtieth of the time required in the case of fresh material.

TABLE M.

Volts Applied.	Time of Breakdown.
7,500	0·0 seconds
7,000	8·5 "
Fresh Material.	
8,500	6·5 "
8,000	10·0 "
7,500	42·0 "
7,000	8·3 minutes.

In all these experiments it was found that breakdown only very rarely occurs between the flat surfaces of the electrodes, but that it generally takes place at a point just outside, where the curvature of the electrodes introduces an air-gap of about a millimetre. The material here is in a weaker state for two reasons. It is not subjected to the cooling of the metal electrodes to the same extent as if it were in intimate contact with them, and there is considerable evolution of heat due to the maintenance of brush discharge in the air when the stress is sufficiently high for its production. Though the actual gradient may be considerably less than it is between the flat metal surfaces on account of the voltage drop in the air, failure takes place at this point rather than between the flat surfaces in the great majority of cases. The above results show how serious is the weakening, due largely to chemical change, which is produced by the brush discharge when long continued.

It will be understood that if this view be correct electrodes with flat surfaces continued in curves of large radius impose a greater stress on these materials than electrodes with sharper curves, on account of the comparatively large area of insulation subject to the influence of brush

discharge, and that perfectly square edges might impose still less stress. In fact, material was found to fail in 17 seconds using electrodes the edges of which had a curvature of 3 mm., while 22 seconds was required when square edges were used.

The influence on the time of breakdown of the heating produced by the surrounding air and of the less efficient cooling was further investigated by raising the top electrode and thus introducing an air-gap. The electrodes used were of 38 mm. diameter with rounded edges. A small metal disc about 10 mm. in diameter was used to support the top electrode, which made an air-gap of a millimetre over the rest of the material. The average time of breakdown was just the same as before, but puncture did not take place close to the small disc, but through the air some little way from it. It seemed as if with this length of air-gap the weakening effect of the absence of cooling by contact with the electrodes was compensated by the lower stress on the material. Several series of experiments were then made on the effect of air-gaps of various lengths on the time of breakdown, as it is well known what serious damage may be caused by air when enclosed in the insulation of electrical plant operating at a high voltage. The hot ionised air in addition to being the source of gases of strong oxidising properties must raise the temperature of adjacent insulating materials. The result of one of these experiments is given below, small pieces of mica or ebonite being used to raise the upper electrode from the material and so provide an air-gap.

Table N.

Material: Two Thicknesses of Oiled Cloth, No. 12.

(Voltage, 10,000.)

Air-gap.	Time elapsing before Breakdown.
0·00 mm.	42·0 seconds
0·30 „	34·0 „
0·50 „	27·5 „
0·75 „	24·0 „
1·05 „	2 minutes, irregular.

The effect of metal in contact with highly stressed insulation materially retards temperature rise and breakdown by reason of its thermal conductivity and heat capacity. It would be expected that using electrodes of less conductivity the material would fail more quickly. The results shown in Table P were obtained using a pair of wooden blocks covered with tinfoil, which were of the same shape as the brass ones.

As would be expected, the thermal properties of the electrodes are of less importance when the electric stress is so high that breakdown takes place in a few seconds. It would seem to be possible to prevent breakdown, at any rate for a long period, by simply keeping the material cool. Quantitative experiments on the energy of electrification and resulting rise in temperature are described later.

To obtain further information on the relative damage caused by a short application of a high voltage and a long application of a lower voltage experiments were made in the following manner. If a given insulating material be equally damaged at various voltages by being

TABLE P.

Two Thicknesses of No. 12 Oiled Cloth.

Volts.	Brass.	Wood.
9,000	9·5 minutes	50·0 seconds
10,000	48·0 seconds	19·0 "
11,000	16·5 "	10·0 "
12,000	10·2 "	6·2 "
14,000	5·2 "	4·5 "

subjected to a steady application of electric stress till it is about to be punctured, then, just before breakdown, samples subjected to a high voltage for a short time and others to a lower one for a much longer time ought to be equally weakened. If, however, as is usually assumed, a prolonged stress at a lower voltage is more exacting than a short one at a higher voltage the two specimens at the moment when they are about to puncture would be differently weakened. As it is imprac-

TABLE Q.

No. 12 Oiled Cloth (One Thickness).

Voltage.	Time of Breakdown.	Period of Application of Voltage.	Further Period at 6,500 Volts.
7,000	28·6 seconds	14·3 seconds	29·2 minutes
6,000	30·3 minutes	15·1 minutes	9·5 seconds
5,500	81·0 "	40·5 "	0·8 "
		Fresh material ...	28·8 minutes

ticable, generally, to stop a test a few moments before breakdown, it is more convenient to take, say, half the time required to pierce the material at any given voltage. After this treatment the specimens which have been subjected to different voltages in this manner may

be tested at such a voltage as will give a conveniently discriminating time of breakdown.

In Table Q is given the result of one experiment on these lines. Similar samples were tested at 7,000, 6,000, and 5,500 volts, and were found to fail after 28 seconds, 30 minutes, and 81 minutes. Other specimens were then treated for half the above times to the same voltages. In order to equalise the temperature conditions they were then left for the night and were tested next day at 6,500 volts. The time required to puncture is given in the last column. It will be noted that the portion treated to the highest voltage agrees with the test on fresh material.

This weakening effect is most conspicuous on the surfaces of the material where the air has free play and where the destruction of the surface glaze by the brush discharge is greatly facilitated. If more than one thickness of material is tested the inner surfaces protect one another to a great extent, and the weakening does not appear to be so pronounced. The following is a similar test on two thicknesses of the same material:—

TABLE R.

Oiled Cloth, No. 12.

Volts.	Time of Breakdown.	Period of Application of Voltage.	Further Period at 9,000 Volts. 24 Hours Later.
	Temperature, 14° C.		Temperature, 17° C.
9,000	5·4 minutes	2·7 minutes	27·5 seconds
7,000	46·2 „	23·6 „	19·0 „
6,000	>1·5 hours	1·5 hours	12·4 „
6,000	>3 „	3·0 „	12·6 „
		Fresh material ...	30·0 „

ENERGY ABSORBED IN INSULATION.

The irregularity of results in a research of this nature, and the difficulties caused by sensitiveness to temperature and humidity increased the desirability of some new instrumental method of studying the nature of electric stress on insulation. From the beginning the importance of some apparatus to measure the energy loss due to alternating stress on these materials had been kept in view. The most promising method seemed to be the application of the wattmeter method which had been used successfully by Mr. Miles Walker * and

* *Transactions of the American Institute of Electrical Engineers*, vol. 19, p. 1035, 1902.

Mr. C. E. Skinner,* and by Mr. G. L. Addenbrooke.† An electrostatic wattmeter was made for the measurement of these small quantities of energy at high voltages, and the paper by Mr. Miles Walker on the subject was especially useful. The apparatus consists of a Kelvin quadrant electrometer designed to work with several thousand volts between the needle and the quadrants. To make this possible it is necessary greatly to increase the dimensions of the apparatus as compared with the standard Kelvin electrometer, in order to prevent electric discharge from the needle to the quadrants. Thus, instead of a needle of about 1½ in. in length, it is made 8 in., and a distance of 2 in. between the quadrants has been generally used. The potential gradient at the sharp edge of the needle has further been reduced by using a beading of thin metal tubing bent to the required shape. Further details are given in Appendix I. Except for the careful shaping of the needle the apparatus was of the roughest description. It was only intended to be preliminary and to obtain information as to how the design, which was largely guesswork, should best be modified for a more finished instrument. It has proved so satisfactory, however, that though naturally more inconvenient to adjust than a finished instrument, which would have required a considerable time to make, there was no reason why it should not be used for all the work required up to the present, and so save considerable delay. At the same time, valuable experience has been obtained as to the details desirable in a more finished instrument, the construction of which it is hoped to begin before long.

The wattmeter has been used with the voltage between the needle and quadrants one-half of that used on the material under test. This method avoids the ordinary correction for the energy loss in the "current resistance," which is necessary when the instrument is used in any other manner. The half voltage is obtained by connecting the needle to the middle point of the high-tension winding of the transformer, which is in two halves. The equality of the voltage generated by the two halves of the transformer has been tested and the agreement is very good, the difference being about a fifth of 1 per cent. The resistances of the two halves agree equally well. In order to produce the requisite potential difference between the quadrants it is necessary that the current be passed through a non-inductive resistance sufficient to produce a satisfactory deflection. As at present arranged, a deflection of 30 in. is obtained, with 10 volts difference between the quadrants when working on a circuit of 10,000 volts. If the power factor is less than unity a greater voltage must be used to obtain the same deflection. The current may be calculated by placing an electrostatic voltmeter across this resistance, and as the

* *Transactions of the American Institute of Electrical Engineers*, vol. 19, p. 1047, 1902.

† *Electrician*, vol. 45, p. 901, 1900; vol. 51, pp. 811 and 845, 1903. Wien's method, used most successfully by B. Monash (*Annalen der Physik*, vol. 22, p. 905, 1907), has voltage and instrumental limitations. It is not direct reading, which is a great disadvantage when changes are rapid.

main voltage is measured directly by a precision voltmeter, accurate values of the power factor can be obtained (Fig. 3).

It is necessary to have a wide range of "current" resistances, and it is also necessary that these should be variable while the circuit is alive. They have been made of fine wire wound on sheet micanite, and are variable from 1,000 to 200,000 ohms. These, and calibrating resistances, used in series with 2 megohms, which will take if necessary 40,000 volts, are operated by means of long ebonite handles, and have given no trouble since their installation. In addition a switch box for putting these various instruments in or out of circuit is operated in a similar manner. The resistances are protected against a high voltage when the material under test breaks down by a spark-gap in parallel with them, which passes enough current to blow the fuse in the primary circuit of the high-voltage transformer.

One of the first experiments done with this apparatus was to test

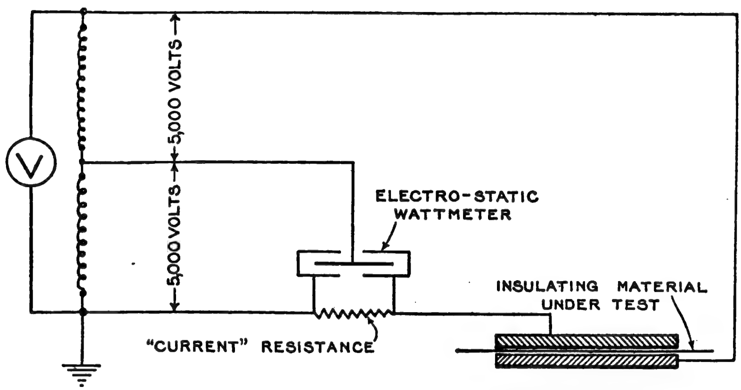

FIG. 3.—Wattmeter Test on Insulating Material.

four thicknesses of varnished cloth No. 12 between the electrodes at 12,000 volts. As it was known that the material would fail, if at all, just over the edge a ring of mica with a hole 1¾ in. in diameter was placed on the lower electrode, and a disc of aluminium of the same thickness as the mica was placed in the hole to bring the surface level. The initial watts were 4·3, and as this energy was employed in warming the material, the electrodes and the air at the edge, where slight brush discharge took place, the temperature gradually rose with consequent increase in energy loss in half an hour to 5·1 watts, in an hour to 6·2 and in an hour and a half to 7·3.

At this point the voltage was raised to 13,000, and local arcing which scorched the material took place suddenly, by a discharge which occurred in the usual place just beyond the flat part of the electrode, without piercing through the mica. The experiment was stopped before puncture took place. This interesting result, the

destruction of the material by the capacity current alone, as the mica may be considered to have an infinite ohmic resistance, seemed to be of very great importance, and other experiments on the point are described later. A second experiment was done at 10,000 volts on four

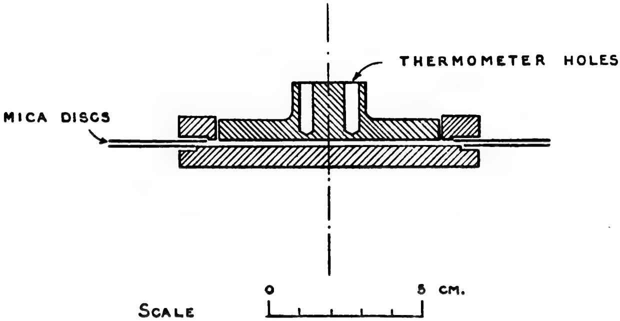

FIG. 4.—Guard-ring Electrodes.

thicknesses of varnished cloth No. 7, with a mica ring above and below it, with aluminium discs fitting them as before.

The watts initially were 8·0, rising to 9·0 in 10 minutes, 10·0 in 20 minutes, 12·8 in 30 minutes, and puncturing occurred in 37 minutes at 17·8 watts, the rate of rise at the end being more than 10 times what it was at the beginning. Puncture took place in this case within the mica rings.

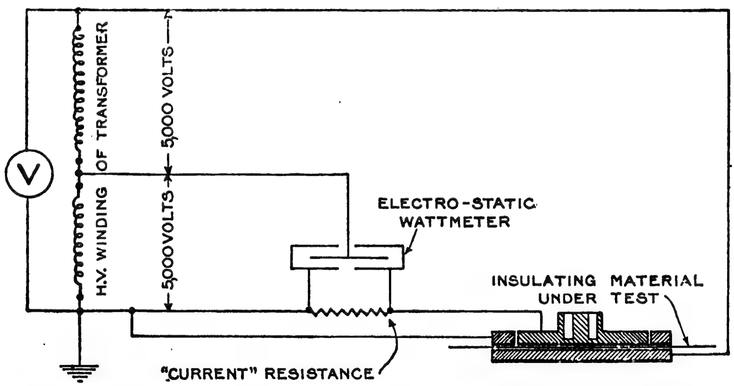

FIG. 5.—Wattmeter Test using Guard-ring.

These experiments were very promising, as giving an indication of what was happening to the material under test. At the same time, it was not possible with this arrangement to say what was the heating effect per square centimetre of the material, as it was obvious that a con-

siderable amount of the energy was being dissipated in the air at the curved part of the electrodes. The device was adopted of dividing one electrode into two concentric ones with a small air-space between them (Fig. 4). The current taken by the outer could be supplied by the transformer direct, and that taken by the inner one alone measured (Fig. 5). This is the principle used in Kelvin's disc electrometer, and also in Price's guard-wire method used in insulation resistance measurements.

The same arrangement of mica rings was adopted, the electrodes being cut away the required amount, and the hole in one ring was made slightly smaller than the other, so that the sharp edges of the metal did not come opposite one another. Failure generally occurred under the guard ring, as it probably reached a somewhat higher temperature on account of the discharge in the air at the edge. Although the area was less than that of the central disc, when testing varnished cloth at 10,000 volts, the watt loss *via* the ring was the higher.

	Area.	Watts.
	Centimetres.	
Central disc	40·5	2·8
Outer ring	33·4	3·5

Effect of Atmospheric Temperature.

Experiments show how a low atmospheric temperature diminished the rate of temperature rise by the reduction in the initial watts, and so delayed the rupture of the material.

A few degrees in the atmospheric temperature may make all the difference as to whether insulation will endure for a very long time or

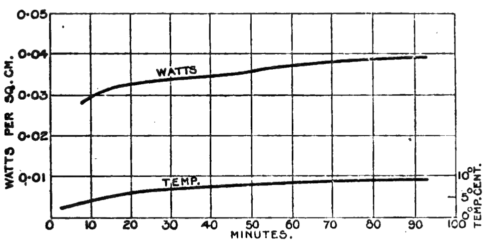

Fig. 6.—Test on Insulating Material at 1° C.

will inevitably fail within, perhaps, an hour, or even a few minutes. The wattmeter shows perfectly what the course of the experiment is likely to be. The results of two typical experiments are shown in the following curves. In the first diagram is shown the course of an experiment on oiled cloth at a low temperature (Fig. 6). The initial

watts were 0·028 per square centimetre, and gradually rose to 0·039, becoming very nearly steady at this value. The temperature of the electrode rose from 2·2° to 9·4°, changing only 0·2° in the last 10 minutes, while the air temperature remained between 0° and 1° during the time of the experiment.

This was the third prolonged application of the voltage to these samples at a similar temperature, one being for 1¾ hours, when a final temperature of 8·2° was reached, and one for 2¼ hours, with a final temperature of 7·8°, the air temperature being 2° below zero.

The second curve shows the result of a similar experiment done at an air temperature of about 15° C. (Fig. 7). In this it will be seen that the initial watts were about 0·04 per square centimetre, as against 0·028

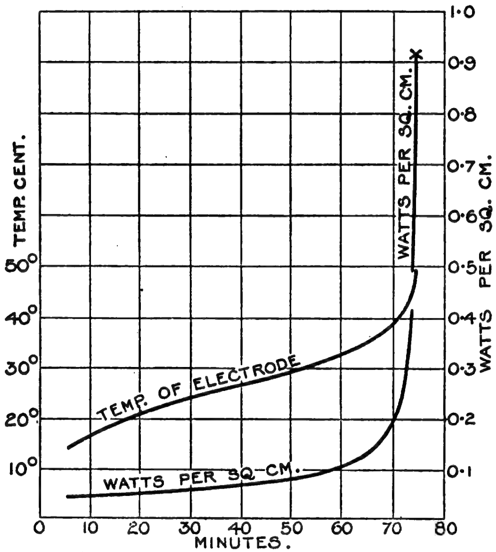

FIG. 7.—Test on Insulating Material at 15° C.

at about 2·0° C. From the shape of the initial part of the temperature curve the natural cooling would have been sufficient to prevent the continual rise of both watt and temperature curve had not the rapid increase of energy loss with temperature been so great that at about 40 minutes there is a point of inflection in the temperature curve, which becomes "explosive" with the concave side uppermost. The watt-meter gives unfailing notice of the impending breakdown of the insulating material, which in this case took place 25 minutes later. The exceedingly rapid rise of the watt curve in the last few minutes is especially remarkable, the final value being twenty times the initial, while half the rise takes place in the last half minute. The large heat capacity of the electrodes prevents the same rapidity of temperature

rise, but the upward tendency of the curve in the last few minutes is very pronounced, the temperature reaching 50° C.

Effect of Desiccation.

Samples of the same material were dried in a desiccator for 22 hours over calcium chloride. They were then tested at 10,000 volts, and the heating effect was found to be reduced to about one-third of what it was in the experiment last described, the test being made at atmospheric temperature (Fig. 8). The consequence is, that the loss by radiation and convection is sufficient to balance the internal heating, and the material could endure a very long time. It is, in fact, in air at a temperature of 15° in a condition similar to that of the undried material at 0°. These specimens have been run for periods aggregating many hours at intervals over several months with very little alteration. As with all these materials, they adhere to one another and to the electrodes by slight pressure and under the influence of

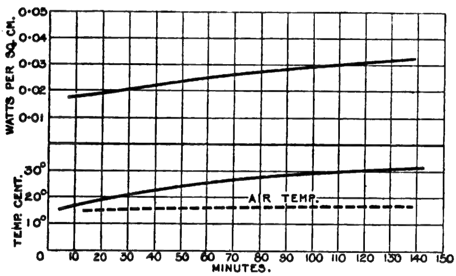

Fig. 8.—Test on Insulating Material at 15° C. (after Desiccation).

high electric stress, and they have been kept in this condition in a desiccator when not under test.

Use of Mica Sheets to Prevent Disruptive Discharge.

An experiment was made using two thin mica sheets completely covering each side of the varnished cloth in a manner similar to an arrangement already mentioned. These sheets were such that they would just stand 10,000 volts alone. By this means it was expected that a much higher temperature would be reached, which experiment showed to be the case. As the temperature rises the material tends to buckle. This introduces a variable air-space, and consequently irregular wattmeter reading. In the experiment (Fig. 9), the buckling was at first largely prevented by the addition of weights. The curve A represents the results of a preliminary experiment without the use of the mica discs. The curve B was obtained after putting the discs in position. It is noteworthy how very little effect the addition of the protective mica has on the watt loss at a given temperature of the electrodes.

Doubtless this is partly accounted for by the insertion of the mica diminishing the cooling effect of the electrodes. The material was examined when the temperature was about 100° C., and showed little sign of damage. The experiment was continued about 40 minutes longer without the extra weights. The watts were somewhat higher and the temperature rose more quickly. The experiment was stopped on the thermometer in the top electrode attaining 120° C. The cloth was found to be distinctly scorched. The curve of watts shows a very marked peculiarity. It rises normally for about half an hour, very rapidly attains a maximum, then drops and varies irregularly about a fairly steady average value. This rapid rise and fall must, I think, be due to the driving out of loosely-held water at about 100° C.

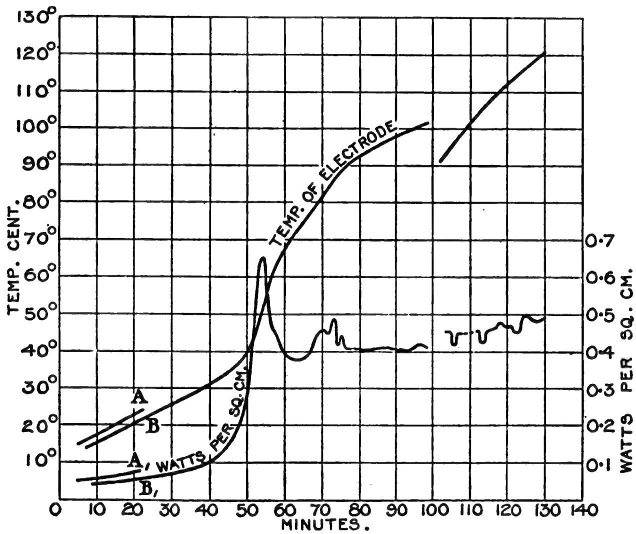

FIG. 9.—Test on Insulating Material between Sheets of Mica.

The temperature curve faithfully reflects these changes. It will be noted that the temperature, when the rapid rise in the watt curve takes place, is about 60°, which would give a difference of about 40° between the temperature of the material, which is assumed to be about 100° C., and that of the thermometer. Considering the low thermal conductivity of the material and mica sheets, and the large heat capacity of the electrodes, this seems not improbable. On this supposition the final temperature would be 160°, as the thermometer registered 120° C. The two other curves shown in Fig. 10 illustrate similar experiments. The material was the same, and buckled more than in the above experiment, as the additional weights were not used. In the first experiment the initial watts were 0·043, which rose to a maximum

of 1·0. The experiment was interrupted at intervals to examine the material, which gradually scorched to a dark brown colour. The temperature was estimated to be not far from 200° C. In another experiment, in which the scorching was not carried to so dark a tint, the temperature registered by the thermometer was 155° C. In the second curve is given the result of a short test of about 20 minutes on one thickness of the same varnished cloth, which was slightly discoloured, when the experiment stopped. Experiments were also done with no material between the two mica sheets. In this case the watts fall slightly at the beginning of the experiment, and then remain perfectly steady. Another experiment was done with the addition of a piece of mica of the same thickness as one sheet of the varnished cloth. The results of these experiments are shown in the dotted lines.

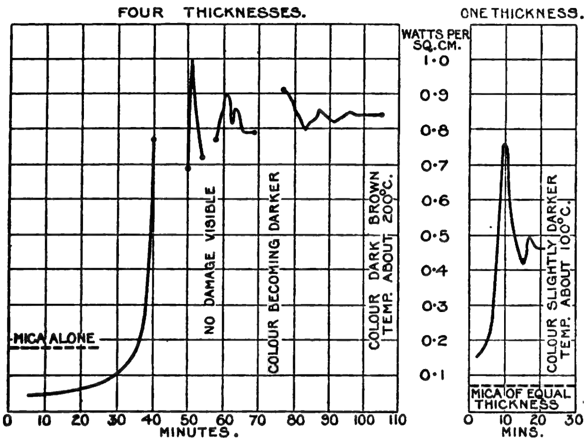

FIG. 10.—Test on Insulating Material between Sheets of Mica.

Experiments on Critical Strength and Energy Loss in Air.

All these experiments demonstrated the importance of the brush discharge in the air, when stressed above its breakdown point, in promoting temperature rise and serious chemical change, when long continued. A lengthy series of experiments was done to determine the potential gradient at which the consequent energy loss in air commences, and measurements were also made of the power lost as the stress is raised above this critical value. The results would have formed a not unimportant part of this report, but a paper on the subject was read by Mr. E. A. Watson,* and the results accorded so well with his, which were obtained by continuous potentials, that they were described in the discussion on Mr. Watson's paper. In addition to the experiments on the effect of high electric stress in air between a concentric tube and wire as described in this discussion, others were

* *Journal of the Institution of Electrical Engineers*, vol. 45, p. 5, 1910.

done in a manner similar to those on varnished cloth. A layer of air was substituted for the cloth between the two sheets of mica, by interposing small distance-pieces of mica or ebonite of measured thickness between the two sheets of mica, which were as thin as would withstand the voltage used, 10,000.

The sheets of mica used were 0·05 and 0·08 mm. thick, and the air-space varied from 0 to 1·5 mm.

The results are shown on the curve line A (Fig. 11). On the same curve is shown the result of a similar test more nearly conforming to commercial conditions. The same voltage, 10,000, was applied to a sheet of micanite about 0·75 mm. thick, and an air-gap put in series with it in a similar manner. The results showed a similar rise in watts as the air-gap was increased up to about 1·6 mm., curve B. As the micanite was much thicker than the mica used in the first experiment,

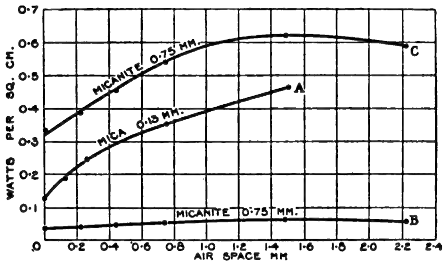

FIG. 11.—Energy Loss when Testing Mica and Micanite with Variable Air-gap.

the actual watt loss is much less. The general shape of the curve is, however, seen to be the same in curve C, which is curve B with the ordinates multiplied by 10.

MICANITE.

In testing micanite, etc., at different voltages the increase in the energy loss due to the brush discharge in the air at the edge of the electrodes is greater than the rate of increase generally over the surface of the insulating material, which is approximately in contact with the metal electrodes. For instance, the results of experiments of the energy loss with micanite 0·75 mm., separating the electrodes at 10,000 and 15,000, work out as shown in Table S.

These figures show how great the heating of the air and insulation over an area surrounding the metallic electrodes may become, when voltages up to about 50,000 are used in testing thick micanite board. In fact, in testing both pure mica and thick micanite in air, the material very rarely fails between the electrodes, but at an indefinite distance, up to perhaps 50 mm., away from the metal in the case of thick micanite, and to about half the distance in the case of thinner mica.

A large amount of work on the testing of micanite has been done at the Laboratory, especially on behalf of Government departments, the general results being briefly as follows: The heating caused by the brush discharge in air, especially when high voltages and thick materials are used, has been found to be very serious. The material becomes rapidly hot and softens around the electrodes, swells by internal vapour pressure, and is finally pierced. It is well known that immersion in oil in general greatly reduces the electric strength of good insulators, the breakdown voltage often being reduced by 50 per cent. In the case of thick micanite, however, this effect is often more than counterbalanced by the almost entire extinction of the brush discharge. In the case of thinner qualities immersion in oil is generally of little or no value. Very much depends on the quality, and the effect of immersion in oil cannot be predicted in the case of ordinary commercial micanite. For instance, while thick boards of ordinary brown commercial micanite, 2·5 mm. thick, generally give

TABLE S.

	Watts per Square Centimetre of Surface of Electrode.	Watts per Linear Centimetre of Circumference of Electrode.
10,000 volts... ...	0·0375	0·0523
15,000 volts... ...	0·0595	0·2170
Ratio	1 : 1·6	1 : 4·1

better results by being immersed in oil, it has been found that similar thicknesses with the adhesive material largely pressed out give worse results in oil.

Generally speaking, thin qualities up to about 1 mm. will withstand a stress of 20,000 volts per millimetre in air for 10 minutes. Above this thickness, up to 2·5 mm., there is more difficulty in making material which will withstand this stress, and usually the material withstands the voltage longer under oil.

MICA.

As mica in various forms is so largely used in electrical plant, a number of experiments have been done on it, in the hope of obtaining some definite information as to the time effect of electric stress upon it. This was known to be small. Mica may be run very near the breakdown point for a long time, and is unaffected by ordinary temperatures met with in machines. In making watt tests on mica, it was found that though the material heated, probably almost entirely owing to the brush discharge in the surrounding air, yet the watt loss did not increase with time—a very different result from that obtained when using oiled cloth.

Disruptive Tests on Mica, in Air and Oil.

Tests in air on pure mica are limited to comparatively small voltages and thicknesses of material. Sheets of mica are limited in size to 6 or 8 in. and in thicknesses above 0·2 mm., sparking round the edge takes place above about 18,000 volts. Mica and its preparations are associated with surface brush discharge to a much greater extent than organic materials such as varnished cloth. A considerable number of observations have been made on mica under these limitations. Ordinary micrometric apparatus was not sufficiently sensitive enough to measure the thickness of many of the sheets used, and an arrangement involving the use of a very sensitive optical lever was devised which magnified

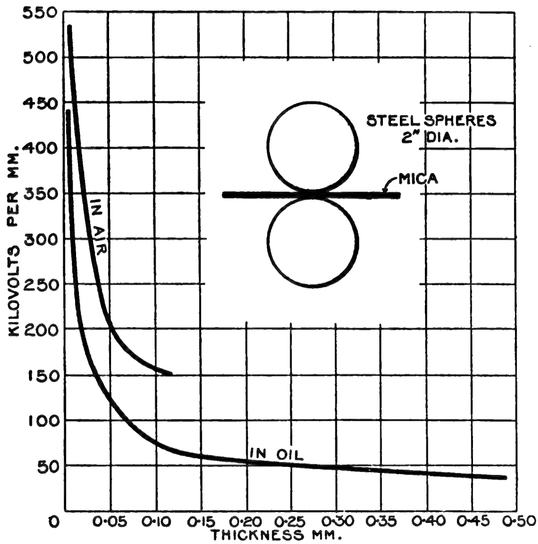

Fig. 12.

the thickness about 10,000 times. By this means measurements could be made of mica as thin as 0·003 mm. (0·00015 in.).

The results are shown in the upper curve in Fig. 12. In the case of the thicker sheets it is only possible to make one puncture in air, but afterwards a large number could be made on it under oil. It must, however, be borne in mind that, as in the case of micanite, the material very seldom fails where it is in contact with the metal electrodes, but at a distance up to 25 mm. away.

In these experiments on mica the electrodes used were two steel balls 50 mm. (2 in.) in diameter. They were used in order to make a considerable number of tests on each sample. At 9,000 volts tests may be repeated under oil at 1·5 cm. from a previous puncture.

The lower curve shows the average result of testing under ordinary transformer oil, which was kept in a tank about 2½ ft. square, and no particular care was taken to keep it perfectly dry. The results in general show an electric strength about one-half that in air.

Time-voltage Tests on Mica, in Air.

The effect of a long time of voltage application appears to have a weakening effect, which is probably mostly due to temperature rise. For instance, a sheet of mica 0·040 mm. thick which failed at 10,000, 10,200, and 10,400 volts, when the voltage was raised to these values in about 20 seconds, was subjected to 8,000 volts and failed in 70 seconds. Another place was subjected to 7,000 volts and the material held up for over 2 hours and was not punctured. The steel balls were too hot to hold and the brush discharge stained the mica with a ring of iron oxide. Other experiments have produced failure in a few minutes on the application of a voltage of about 10 per cent. less than that which produces failure in 20 seconds. A somewhat lower voltage seems to be withstood for a very long time.

Mica under Oil.

The general result of a large number of experiments shows that under oil mica will stand for a long time a voltage very little below that which will puncture it in a few seconds. At first it was thought that no damage was sustained by the material, but it was found that a faint ring was often etched on the surface of the mica. The cause is no doubt due to the formation of corona in the oil and under the conditions, 9,000 volts on a sheet 0·2 mm. thick, there has not been enough energy to maintain it on both sides of the mica. With 2 in. spheres the diameter of the ring on the mica at about 9,000 volts is about 8 mm. Experiments have been made to see if there were a discontinuity in the watt-volt curve of mica under oil. If the corona forms at a certain electric stress, a measurement of the watts as the voltage is raised might be expected to show a discontinuity in the rate of rise at this point. Though the watts rise very rapidly no such definite point has been detected.

Pertinax Insulating Material.

This material was kindly provided for the purpose of this research by the firm Meirowsky, of Cologne. It is made by rolling thin paper on a mandrel. During the process the paper is covered with hot varnish and the excess is squeezed out by a heavy roller. The material forms a tough and strong form of insulation suitable for many purposes. It was supplied in the form of tubes of 8, 5, and 3 mm. bore, and all of 11 mm. external diameter, the walls being 1·5, 3 and 4 mm. thick. The tubes were 50 cm. long. They were tested by applying the voltage between mercury which filled the hole and a layer of tin foil tightly wound round the middle of the tube for a length of 34·5 cm. The tinfoil was practically at earth potential.

The effective surface of the tinfoil was 120 sq. cm., and as the tubes were all of the same outside dimensions the diagrams have been plotted with watts per square centimetre of outside surface of ordinates. The heating, as in previous experiments, is entirely due to insulation losses, no attempt being made to heat the inner conductor by passing a current through it or otherwise. In the tests with the tube of largest bore the temperature of the top of the mercury could be determined by floating a thermometer in it. Owing to the heat capacity of the mercury, there is a time lag of the thermometer when the watts are large and rising rapidly and the thermometer continues to rise for a short time after failure takes place. The readings of the thermometer in the mercury at the end of the experiments at 4,000, 3,500, and 3,000 volts were 28°, 22°, 21°; and the air temperature was 19, 18,

PERTINAX TUBING.

Thickness 1·5 mm.

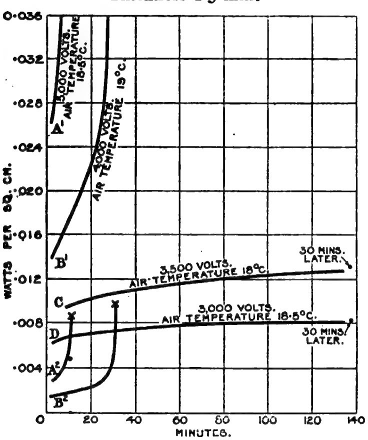

FIG. 13.

Thickness 1·5 mm.

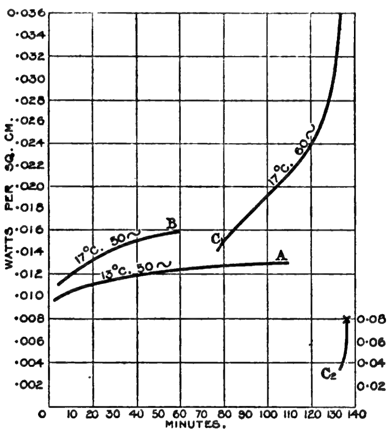

FIG. 14.

18·5 respectively. Fig. 13 shows the results of experiments at 5,000, 4,000, 3,500 and 3,000 volts on the Pertinax tube of largest bore. The curve A_1 repeated and continued in A_2 on $\frac{1}{10}$ the scale of ordinates show the effect of the application of 5,000 volts producing failure in 12 minutes. B_1 and B_2 are the results at 4,000 volts, failure resulting in 31 minutes, while C and D are tests of 160 minutes at 3,500 and 3,000 volts.

The curves in Fig. 14 show results obtained on a similar tube at 3,750 volts. This voltage was chosen, as the previous experiments indicated that it was very near the dividing line between destruction and comparative immunity. The lower curve A shows the results of a run of 110 minutes, 50 cycles, at an air temperature of 13° C. From the shape it appears that the material would stand this for a very long time and perhaps almost indefinitely. However, as only

slight alteration in the conditions would probably be required to produce the condition leading to failure, the air temperature was raised from 13° to 17°, and another run of an hour made (B). This also showed that the material would most likely hold out a long time, so after a rest of 14 minutes the same voltage was again applied and the frequency was increased from 50 to 60 cycles per second. In a few minutes the curve of energy loss in the insulation takes the form associated with failure in a comparatively short time (C_1 C_2). The internal heating goes on at a continually increasing rate till the material fails at 66 minutes after the application of the voltage at 60 cycles. This experiment indicates very clearly the difference between

PERTINAX TUBING.

Thickness 3 mm.

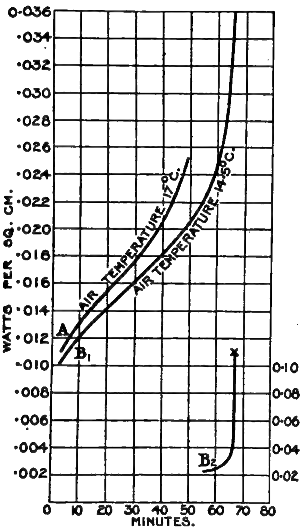

FIG. 15.

Thickness 4 mm.

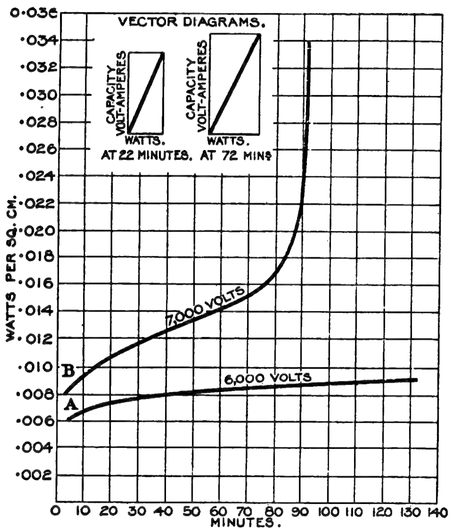

FIG. 16.

these insulation losses under alternating potentials and losses due to a resistance effect alone. The latter would be independent of the frequency, while most of the tests on these materials which have been made to determine the effect of frequency indicate that, when working under the potential gradients met with in practice, a large proportion of the loss is proportional to the number of cycles of alternating stress in a given time and therefore of the nature of a hysteresis effect.

Fig. 15 represents the result of two tests on thicker Pertinax tube with 5 mm. hole. The upper curve A shows the progress of an experiment at 17° C. The curve predicts inevitable failure, but the test was stopped before this took place. Next day it was repeated and the curves B_1 and B_2 were obtained (the latter with the scale of

ordinates reduced to one tenth). It will be noted how similar are the forms of the two curves—the difference between the two being accounted for by the difference of $2\frac{1}{2}°$ in the atmospheric temperature. They show the important result that though the material at the end of the first experiment A was within 8 or 10 minutes of failure, a second run under the same conditions shows no evidence of permanent weakening.

Fig. 16 shows the result of a test on the thickest walled Pertinax tube. The lower curve A represents the course of an experiment at 6,000 volts for 130 minutes, and the upper curve gives the result of a second experiment on the same tube at 7,000 volts. These curves are similar to several previous ones.

An interesting point in connection with this increase of dielectric loss with temperature is the relative variation of the electrical properties of the material. A condenser with internal losses may be divided in imagination into a perfect condenser without loss together with a resistance in series of such a value that the watts generated in it by the charging current are the same as in the actual condenser under consideration. A good condenser corresponds to an imaginary perfect one with a small resistance in series, and a condenser with larger internal losses is equivalent to one with a larger series resistance. If, in addition, the condenser has so low an insulation resistance that there would be an appreciable energy loss with a continuous voltage, an additional resistance must be added in parallel with the condenser and its series resistance. In the case of ordinary insulating materials this source of loss is probably small in comparison with the loss due to reversing the polarisation of the dielectric. The expression "leaky condenser" is here avoided as representing one which would show appreciable conductivity and energy loss under a continuous voltage. A condenser with internal losses is dynamically equivalent not only to a resistance in series with a perfect condenser, but also to a perfect condenser with a resistance in parallel, in which the energy loss is equal to the loss in the condenser under consideration. In general the losses in a dielectric may be considered as due to the two causes, a condenser and series resistance effect and condenser and parallel resistance effect. The ratio of the two would be largely dependent on the temperature as the leakance in the materials tested has been found to increase very rapidly with temperature. However, the conception of a condenser with series resistance seems more nearly to represent the physical condition of ordinary insulating materials.

From this point of view a dielectric may be considered to be not a single condenser with a series resistance, but an immense number of very minute condensers, perhaps of molecular dimensions, each with a series resistance. The whole thickness of the dielectric would be made up of an almost infinite number of such condenser and resistance systems in series. In practice we can but obtain a measure of the single equivalent condenser and resistance.

As the insulation is heated the energy loss increases rapidly. If, as

seems probable, the dielectric does, to some extent at any rate, consist of a system of condensers and resistances in series and the comparison is not simply a broad analogy, then it is of great importance to attempt to form from the result of experiment a theory of the physical basis of these changes.

The observations made in course of the experiment shown in curve B, Fig. 16, may be analysed as an example. The change in the quantities measured is considerable; but the rate of change has not been too great to prevent accurate observation over a considerable part of the experiment. The following table shows the results of observations at 22 minutes and 72 minutes, the values being those measured and not in watts per square centimetre (120 sq. cm.) as in the diagrams. The vector diagrams are shown in the inset. In the interval the watts increased by 44 per cent. and the capacity volt-amperes by 25 per cent.

	22 Minutes.	72 Minutes.
Volts	7,000	7,000
Amperes	0·000464	0·000595
Volt-amperes	3·250	4·170
Watts	1·291	1·863
Power factor	0·397	0·447
Capacity, volt-amperes	2·980	3·730
Equivalent Perfect Condenser and Resistance in Parallel.		
Capacity of condenser, microfarads ...	$193{\cdot}6.10^{-6}$	$242{\cdot}5.10^{-6}$
Resistance, ohms	38.10^{6}	$26{\cdot}3.10^{6}$
Current in condenser	0·0004260	0·000533
Current in resistance	0·0001845	0·000266
Equivalent Perfect Condenser and Resistance in Series.		
Capacity of condenser, microfarads ...	230.10^{-6}	351.10^{-6}
Resistance, ohms	$5{\cdot}98.10^{6}$	$5{\cdot}26.10^{6}$
Voltage on condenser	6,430	5,400
Voltage on resistance	2,770	3,130
$\frac{1}{K\omega}$ ohms	$13{\cdot}8.10^{6}$	$9{\cdot}1.10^{6}$

On the theory of a condenser and series resistance, the increase in energy loss as the temperature rises may be due to two causes. The increase may be due to an increase in the resistance, unless this be as large as $\frac{1}{K\omega}$ originally, or to an increase in the condenser capacity.

It might also be due to an increase in the one sufficient to compensate for a diminution in the other. The last four lines of the above table show that this might be the case, but measurements of the leakance at 1,000 volts immediately after the end of the experiment show that with this kind of material the ohmic resistance when the material is warm is not high enough for the leakance to be neglected. Though the series resistance falls from 5·98 to 5·26 megohms the increase in capacity is relatively greater, from 230.10^{-6} to 351.10^{-6} microfarads. This would alter the distribution of voltage between the two so that the actual watts are increased.

The measurement of the electrical properties of solutions of salts shows also an increase of capacity and diminution of resistance with rise of temperature, which indicates that, in organic materials, the energy loss is probably largely of an electrolytic nature.

From the above considerations it will be seen that whether the energy loss increases or diminishes with rise of temperature will, assuming negligible leakance, depend on the relative change of K and the series resistance R. If the increase in K is not so large as in the material on which the above experiments were made, it may happen that the diminution of R is sufficient to lower the energy loss as the temperature rises. This actually happened in a piece of gutta percha cable tested at 4,000 volts.

GUTTA PERCHA CABLE.

Internal diameter, 1·25 mm. External diameter, 4·5 mm.
Length, 7·3 metres. Frequency, 50.

Temperature	7° C.	19·5° C
Volts	4,000	4,000
Watts	0·270	0·235
Amperes...	0·00144	0·00152
Volts-amperes	5·76	6·08
Capacity, micro-microfarads...	1,150	1,210
Power factor, cos ϕ	0·0468	0·0386
$R = \frac{\cos \phi}{K \omega}$	130,000	102,000

From the above it will be seen that though the capacity and amperes have increased so that C^2 has increased 12 per cent., yet the diminution of R_s has been relatively greater, so that the energy loss is less at the higher temperature. In the case of gutta percha, though the true leakance increases very rapidly with temperature, it is so small as to be negligible compared with the polarisation loss.

It may happen that at one temperature one effect may predominate and at another be relatively the smaller, so that the loss may reach

a minimum at a certain temperature, which seems to be the case with certain high-voltage cables.*

Westinghouse Paper Tubing.

The curves (Figs. 17–22) show the result of a long series of experiments on material supplied by the British Westinghouse Company which was similar to the Pertinax tubing. It was in the form of tubes about 1 metre long with an external diameter of 23·5 mm., and thickness of wall was 1·9 mm. For the purpose of the experiment a tube was cut down to about half its length, being too long for the oven, and it was sealed with a cork at the lower end. A loosely fitting brass tube sealed also at the lower end was placed inside, and the annular space between the two was filled with mercury, a great weight of which was by this means avoided. A thermometer reading to 0·2°, fixed in a cork, registered the temperature of the air in the inner brass tube. The circumference of the outside of the tube was 7·4 cm., and a length of 35·5 cm. was covered with tinfoil. This formed the outer conductor, which had an an area of 260 sq. cm.

The series of experiments were carried out to investigate more accurately the effect of changes of temperature, voltage, and frequency on material of this nature. They have all been done without moving the specimen which was kept in the oven, the temperature of which was maintained steady, generally at about 24·6° C., by a thermostat. The experiments are lettered A to W in chronological order.

Repeated Tests at the same Voltage.—The upper curves A to G (Fig. 17) show the results of a series of experiments at 5,000 volts, an experiment being stopped when the energy developed in the insulation amounted to about 16 watts. It will be noted that there is an apparent progressive weakening after each run, the watt curve rising more quickly. Some of the difference is probably the effect of permanent change, but experience shows that it is mostly due to the slightly higher temperature of the later experiments, and those represented by E, F, G are so similar that probably any appreciable permanent alteration causing a more rapid rise is confined to the first one or two runs. However, all subsequent experiments were stopped at 10 or 12 watts, which seemed to be a safe value. At the bottom of the same figure are results of two experiments at 4,000 volts and two at 3,000, which give a good idea of the rapid rise of energy loss with voltage.

Effect of Change of Frequency.—Fig. 18 shows the effect of frequency. As the voltage, 5,000, used in the previous experiments produced too rapid a rise for convenience, 4,500 was used in nearly all the rest of the experiments. Curve H shows the results of a run at 47 cycles, which was followed by J at 50 cycles and K at 53 cycles. The H conditions were then repeated, and the results gave a curve L, coincident with H for 90 minutes and then slightly above it. The temperatures to the nearest 0·1 are given, but probably a few hundredths of a degree are sufficient to cause such a divergence when the curves are very flat.

* Hochstädter, *Elektrotechnische Zeitschrift*, vol. 19, p. 467, 1910.

This repetition showed that the differences between H, J, K could not be due to successive permanent alterations of the material, but that they are due to frequency alone. The curve M shows the next application of the same voltage at the same temperature, the frequency being 56. The individual observations have been plotted for this experiment. When the source of supply is a battery the curve is perfectly continuous; but when running off a dynamo small variations in voltage and frequency are unavoidable and continual adjustment is necessary, a change in the supply voltage of a few parts in 10,000 being quite noticeable on the wattmeter. Curve N shows the result at a frequency of 38. After the conditions had become very nearly steady the frequency was raised to 50, and after a few minutes to 56.

WESTINGHOUSE PAPER TUBING.

Thickness 1·9 mm.

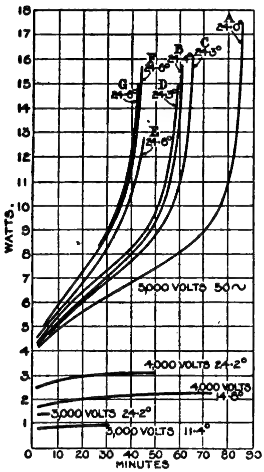

FIG. 17.

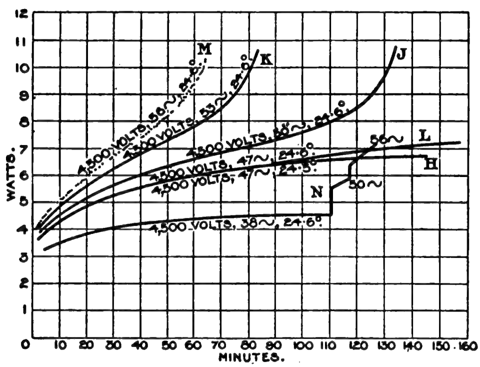

FIG. 18.

Effect of Change of Temperature o, 25°.—After this the temperature was raised from 25° to about 50° and the voltage reduced to 2,250—half its previous value. The result of two experiments at 50 and 40 cycles is shown in curves P and Q (Fig. 19). Curve J at 50 cycles is reproduced for comparison. From these it will be seen that though the initial watts in experiment P are considerably lower than in J yet the rate of increase is much greater, which implies that a small increase in temperature at 50° is accompanied by a greater increase in energy loss than when the same increase of temperature occurs at 25°. This agrees with the results of previous experiments.

Change of Capacity, etc.—Curve R (Fig. 20) shows the result of an experiment lasting 200 minutes at 4,500 volts 50 cycles, and an initial temperature of 24·6. The conditions were similar to S and T, but the

experiment lasted longer, which was probably due to the oven temperature not having become quite steady. In addition to the watt curve some others have been given which have been omitted from the other figures, as it is quite sufficient to show one representative set of them. The numerical value of the ordinates is the same for all the curves; but the position of the decimal point is indicated by the figures given with each curve, showing initial and final values. The watt curve is similar to the previous ones. The lowest curve shows the rate of increase of the watt curve, the ordinates being increased 100 times. This becomes a minimum, 0·011 watt increase per minute, at about 100 minutes, and the subsequent rise predicts failure 1½ hours before the end of the experiment. At the top of the diagram is the capacity volt-ampere curve obtained by subtracting vectorially the watts from the product of the volt-amperes. Under the conditions of the experiment the capacity volt-amperes were about twice the power volt-

WESTINGHOUSE PAPER TUBING.

Thickness 1·9 mm.

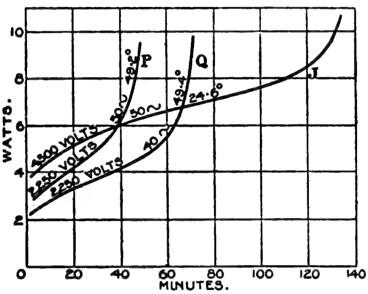

FIG. 19.

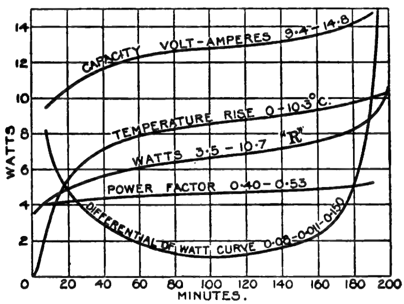

FIG. 20.

amperes; but as the rate of increase is less the power factor increases from 40 per cent. to over 50 per cent. The temperature curve shows the rise of temperature of the thermometer above its initial reading. The rise amounted to 10·3° at the end of the experiment, a figure which agrees closely with other experiments which were stopped at a similar final value of the watts.

Effect of Small Change in Temperature.—The next diagram (Fig. 21) shows the results of two experiments S and T under conditions similar to R. There is a difference of some 7 minutes in 150 between the times at the end of the experiments, which would be accounted for by small unavoidable differences in the conditions. The upper curve shows the temperature rise of the thermometer in the central tube, which agrees with the previous experiment R. Curve U to the left of the diagram shows the course of an experiment under exactly similar conditions, except that the surrounding air temperature was 1·0° higher. The time is reduced to about one-half. In addition to the temperature

curve during the application of the voltage the cooling curve is given after switching off. These two show the effect of a small change in temperature, and the following one the effect of a small change in voltage.

Effect of Small Change in Voltage.—In Fig. 22 is shown the course of two runs—one at 4,500 volts and the other about 2 per cent. higher at 4,600 volts. The effect is to reduce the time to about one-half—almost the same as the effect of 1° increase of temperature.

All these experiments show that if the deteriorating effect of such applications of electric stress as are here described is to be judged by the course of a subsequent application under similar conditions, it is necessary that temperature, voltage and frequency should be the same to a very high degree of accuracy. Under the average conditions of these experiments a change of 1 per cent. in the time of reaching 10 watts would be produced by a change of 4 in 10,000 in the voltage,

WESTINGHOUSE PAPER TUBING.

Thickness 1·9 mm.

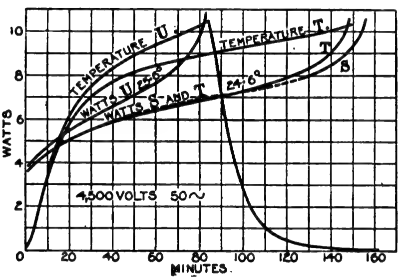

FIG. 21.

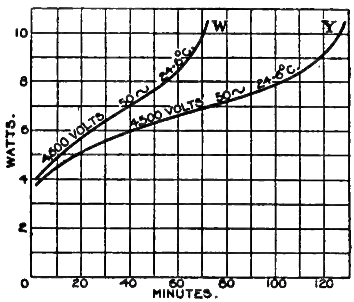

FIG. 22.

or a change of 0·02° of temperature, or a change of 0·1 per cent. in frequency. These limits would require special apparatus for their attainment. The margin of the voltage variation is probably impracticable.

PAPER AND OIL INSULATED CABLE.

The very important question of tests on cables demands special consideration, but the question whether the determination of the energy loss in the insulation would likewise give valuable information as to the electric strength of the insulation under different conditions was of the greatest interest. A short length of $\frac{3}{16}$ paper-insulated cable being available, a few preliminary experiments were made on it, lengths between 1 and 2 metres being used.

The results of two tests at 6,000 volts are shown in Fig. 23, the upper one (A) being at 37° C. and the lower one (B) at 14° C. The cable failed in the former case in 16 minutes, while the latter showed all

signs of withstanding the voltage indefinitely. The small inset diagram gives the result of a series of tests at different temperatures, showing the watts per metre in the insulation after the material has attained a nearly steady temperature by a prolonged application of the voltage. At 6,000 volts, an air temperature approximately 35° was the limit for this piece of cable, when the energy loss amounted to some 4 watts per metre.

These experiments are the results of tests on one sample of cable, and are only given to show that they are quite similar to those obtained on other organic materials. No further experiments have as yet been done on cables. A considerably higher voltage than what has at

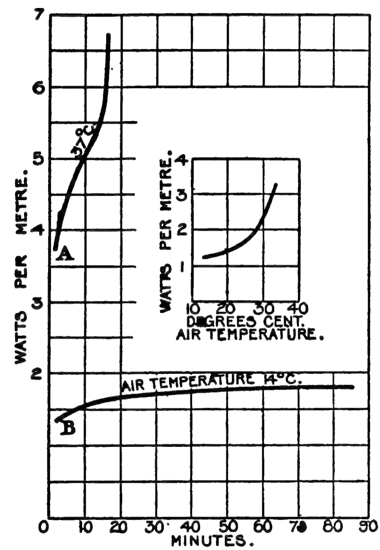

FIG. 23.—Paper Cable at 6,000 Volts.

present been used on the wattmeter would be necessary for further work in this direction.

Indiarubber.—An experiment was also done on rubber cable to obtain some preliminary information on the question of energy loss. A length of lead-covered cable of small section was tested, and between 3,500 and 12,000 volts (failure ensuing at 14,000 volts), the energy loss was quite approximately proportional to the square of the voltage, the power factor being about 20 per cent. In ordinary cables of this class, however, the rubber is not in complete electrical contact with the lead covering, there being a small air-space partly due to the use of a layer of tape. As one of the interesting points to be investigated was the change of energy loss with the temperature, which seems to be small, a probable layer of ionised air was inadmissible, and

experiments were made on a piece of rubber tubing with an electrolyte inside and out. The effective length of the tube was 50 cm., the external diameter 1 cm., and the thickness 1·2 mm. As the result of a series of tests lasting a fortnight, it was found that a progressive increase in energy loss ensued. This increase went on more quickly when the voltage (6,000–8,000 volts) was applied, but was appreciable from day to day when not subjected to voltage.

At 6,000 volts, 50 cycles, the watts initially were 0·44, and at the end 45. The power factor at the beginning was 7 per cent. and nearly independent of the voltage. At the end the watts increased much faster than the square of the voltage and the power factor was 30 per cent. at 2,000 volts and 95 per cent. at 6,000 volts. Repeated attempts to measure the insulation resistance at 1,000 volts (direct-current) showed it to be well above 200 megohms, while at the end the apparent resistance was less than 1 megohm. At the beginning the watts varied nearly as the frequency, while at the end a change in frequency produced practically no change in the watts. This fact pointed to the conclusion that the loss was associated with a true ohmic conductance. Had the expenditure of some 45 watts been due to a few accidental local weaknesses the insulation would have been burnt instantly. It therefore seemed to be a true property of the rubber acquired by long soaking. The only explanation seemed to be that while under a high electric stress, a great reduction in the ohmic resistance of the rubber took place, and that ordinary tests at a few hundred volts might give no indication of this effect.

To test this theory, a continuous voltage, with a Paul micro-ammeter in the circuit, was superposed on the high-voltage winding of the transformer. For the continuous voltage a magneto machine of 250 volts was used. This produced no effect on the ammeter until the alternating voltage reached about 2,000, after which the continuous current passing increased rapidly as the alternating voltage was raised and indicated finally an ohmic resistance approximately equal to that calculated from the wattmeter readings. These observations seem to be novel, but time has not permitted of pursuing the subject farther.

It might be thought that the effect was due to a great change in the ohmic resistance of the rubber due to temperature rise associated with energy losses on the material. The effect, however, is conspicuous when the stress is so low that the temperature of the rubber can be but a fraction of a degree above that of the surrounding liquid, whereas a much greater change of temperature of the surrounding liquid produces but little effect. This property may be found to have considerable technical importance, and the practice of immersing rubber cables intended for high voltages in water for many hours previous to the ordinary tests may be distinctly undesirable.

Rubber has lost much of its importance as a high-voltage insulator, but in view of the large increase in the supply of plantation rubber in the next few years, commercial considerations may lead to its reconsideration. In any case, the physical property of a material acting as a

partial conductor to both alternating and continuous current under high electric stress, when lower stresses would give no indication of conductivity of this magnitude, is one of great importance and is a subject which invites further investigation.

Conclusions.

The results of the experiments on oiled fabrics show that when subjected to voltages sufficiently high to break down the surrounding air, a rapid decrease in electric strength is produced, which is largely due to the damage produced by the brush discharge. This action is the more pronounced when a few layers of material are tested, as the surfaces in contact with the metallic electrodes suffer most. This effect increases with time, and as a comparatively small lowering in voltage corresponds to a great increase in the time required to produce rupture, the effect of a long application is very generally more deleterious than that of a short application of a higher pressure. When tests are made on a few layers of oiled fabrics between metallic plates and the effect of brush discharge at the edge is reduced by mica rings, measurements of the energy loss in the insulation show but little permanent change in many hours. Some air is enclosed in the layers and no doubt the oxygen present is soon used up in oxidising the surface of the materials.

An increase in humidity, temperature, or electric stress results in an increase in the rate of heat production, and the temperature may rise till destruction takes place. Even if the insulating material be protected by sheets of mica, which are sufficient to withstand the voltage, destruction by charring may ensue, and the mica may have comparatively little effect on the rate of heat production.

The results of the experiments on comparatively thick-walled tubes of varnished paper give time-energy curves of substantially the same form. The freedom from air layers renders possible much more certain and accurate comparative tests on the effect of changes of physical condition. The experiments indicate that the temperature rise produced by the electrical heating of the insulation produces but little permanent change, provided the rapid final increase is not allowed to take place. Energy measurements on insulation of this nature give information obtainable by no other means.

An experiment on the energy loss in a paper-insulated cable gives similar results. The literature on the subject in this country does not seem to reflect the commercial importance of the immense outlay involved in large cable systems.

The results of a similar test on rubber point to the conclusion that a great increase in conductivity takes place as the result of the application of electric stress when immersed in water. This increases with the time of immersion, and when the effect has become very marked, it increases very rapidly with the voltage.

In conclusion, I desire to express my great personal indebtedness to the Engineering Standards Committee for their gift of the very complete

generating and transforming apparatus, and to the Committee of the Laboratory for the provision of the voltmeter for 100,000 volts, both of which have been indispensable for the research. My thanks are also due to Dr. Glazebrook and Mr. C. C. Paterson for their interest and advice during the work.

APPENDIX I.

Notes on the Use of the Electrostatic Wattmeter at High Voltages.*

The general theory of the quadrant electrometer used as a wattmeter leads to the equation—

$$W = N K \frac{D}{R} + \frac{N-2}{2} R A^2,$$

where—

W = watts expended in the circuit P Q, in which the power factor may have any value (Fig. 24).

$N = \frac{R_1 + R_2}{R_2}$ = multiplying power of the dividing resistance used to supply the needle.

K = the constant of the instrument.

D = the deflection produced.

R = the resistance, through which the main current is passed to produce the difference of potential between the quadrants.

A = current through R.

If $N = 1$, the needle being supplied at the full voltage, the instrument measures half the watts lost in R in addition to the load P Q.

If $N = 2$ the instrument measures ½ the load A B directly, as the term depending on the energy loss in R vanishes.

If $N > 2$ then the instrument measures $\frac{1}{N}$ of the watts in P Q, less the watts lost in R multiplied by some factor. This factor is less than unity if $n < 4$, and greater if $n > 4$. If the actual watts be therefore small and the power factor low, so that the current is relatively high, the value of $\frac{N-2}{2} R A^2$ may be considerably greater than the effect on the wattmeter of the energy in P Q, so that the reading of the instrument may become negative, and accurate measurement of the current has to be made in order to calculate the correction due to the energy loss in R.

* A. Russell, "Theory of Alternating Currents," vol. 1, p. 194. M. Walker, "The Electrostatic Wattmeters in Commercial Measurement" (*Transactions of the American Institute of Electrical Engineers*, vol. 19, p. 1035, 1902). C. E. Skinner, "Insulating Material" (*Transactions of the American Institute of Electrical Engineers*, vol. 19, p. 1047, 1902). E. Orlich and H. Schultze (*Zeitschrift für Instrumentenkunde*, vols. 23, p. 97, 1903; 27, p. 65, 1907; 1908; and 29, p. 33, 1909).

The very great convenience of having the instrument direct reading led to the choice of working with the needle at half the supply voltage. N in this case being 2, the correction for the "current" resistance vanishes.

For use with 5,000 volts or more between needle and quadrants, the one point of importance requiring consideration is to keep down as far as possible the electric stress in the air surrounding the needle and suspension, so as to raise as far as practicable the voltage at which brush discharge becomes appreciable. This entails a large air-gap between the needle and quadrants and a correspondingly large needle. A distance of 2 in. between the quadrants has been found quite satisfactory for circuits up to about 15,000 volts. The needle was made 8 in. long with the idea of using somewhat larger quadrant separation for higher voltages when desired. It is made of thin sheet

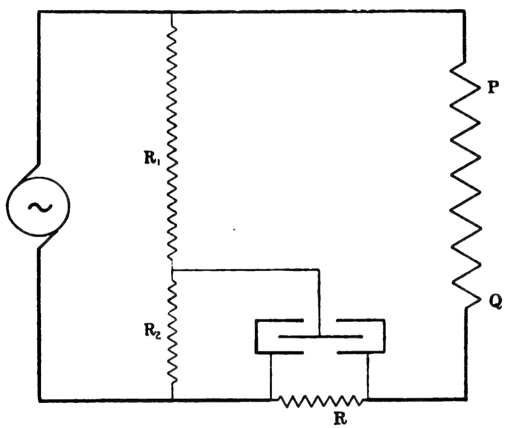

FIG. 24.

aluminium alloy, and the edge of it is formed of thin copper tubing ¼ in. in diameter, in order to diminish the electric stress in the surrounding air. This has made the moment of inertia very large compared with that of needles for instruments designed for use at ordinary voltages, but the larger forces due to the high voltage afford considerable compensation.

The quadrants have been made by pasting tinfoil on two sheets of plate glass and cutting away two strips 3 mm. wide at right angles. The glass plates have holes 2 in. in diameter through their centres for the suspension and damping arrangements. The damping may be conveniently adjusted by using a mixture of glycerine and water, with a layer of oil on the top to prevent further absorption of water from the atmosphere. The suspending wire is surrounded by a tube at the same potential, to reduce the electric stress in the air surrounding it. The shape of the needle was made such as

it was hoped, would give a very even calibration curve. This has been found to be actually the case, as the following table shows. The change of constant over a wide range of voltage is quite small. The watts are calculated from the formula $W = 2\,K \times \frac{D}{R}$, D being the scale reading, R = the "current" resistance. The value of 2 K is found by observing the deflection on a known load. The load is a convenient number of the voltmeter resistance boxes. In series with these is a two-dial resistance box with resistances 10 × 100 and 10 × 1,000 ohms,

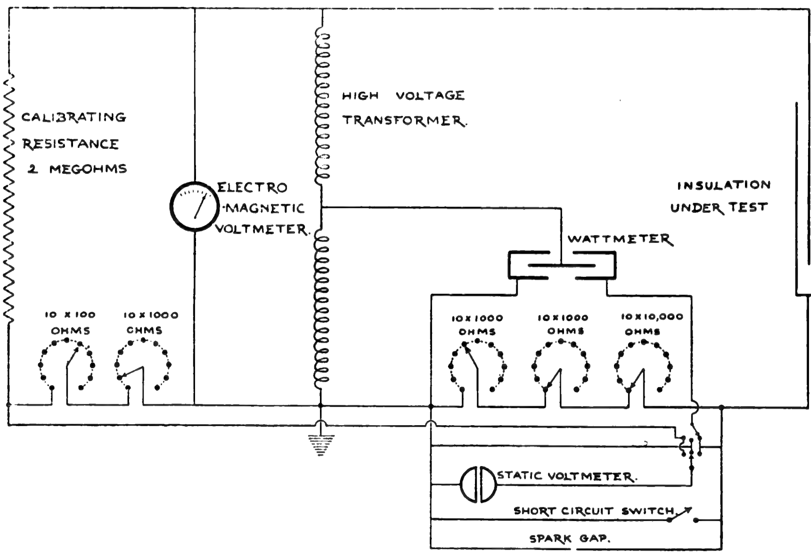

FIG. 25.

across which the quadrants are connected. By varying these resistances the scale may be calibrated at as many points as may be desired. For example, using a load of 2 megohms at 10,000 volts, equivalent to 50 watts, and a resistance in series of 1,600 ohms the deflection produced was 22·93 divisions (1 division = 2 cm.), giving a value for 2 K of 3,490. The effect of 1,600 ohms in series with the 2 megohms really reduces the 50 watts in the load very slightly, but this may be neglected for ordinary purposes.

ELECTROSTATIC WATTMETER, 10,000 VOLTS.

$$\text{Watts} = 2\,K \times \frac{\text{Deflection}}{\text{Resistance}}.$$

Value of 2 K for various scale readings.
Scale distance 2 metres, one scale division = 2 cm.

Scale Reading.	2 K.
5 divisions	3,490
10 "	3,505
15 "	3,505
20 "	3,495
25 "	3,480
30 "	3,465

The factor 3,490 means that using a "current" resistance of 3,490 ohms 1 division (2 cm.) on the scale corresponds to 1 watt. If the resistance is, say, 20,000 ohms the scale value is $\frac{3{,}490}{20{,}000}$, or 0·1745 watt per division.

APPENDIX II.

SOURCES OF ERROR IN AN ELECTROSTATIC WATTMETER WHEN USED TO MEASURE POWER AT HIGH VOLTAGES.

Errors due to Current Resistance.—In measuring the energy loss in small quantities of insulating material the current is very small, and the power factor being low it is necessary to use high "current" resistances to obtain a fair deflection on the wattmeter. This introduces two sources of error.*

The addition of a large resistance in series with a condenser, such as is formed by insulating material between sheets of metal, slightly reduces the current; but a more important effect is that the phase relation of current and supply voltage is altered. It can be seen that the effect on a leading current of an added resistance is to reduce the angle of lead, and when the power factor is low this effect may become very important. The wattmeter gives too high a reading depending on the value of the current resistance.

Another source of error is the effect of the high resistance on the potential of the quadrants which are not connected directly with the terminal of the transformer (Fig. 24). On account of the high potential of the needle a considerable capacity current passes along its suspension, and a corresponding current is divided between the two sets of quadrants. The one set is connected directly to one terminal of the transformer; but the capacity current induced in the other has to traverse the current resistance. The effect is that the quadrant is prevented from reaching the potential it otherwise would do, and on open circuit a deflection is produced depending on the value of the resistance used. This deflection may amount to about 5 per cent. of the total length of the scale. These two errors depend on the value of the current resistance. If this could be reduced to zero they would disappear. However, as the errors are practically proportional to the resistance, they may be eliminated by taking the instrument readings

* E. Orlich, *Zeitschrift für Instrumentenkunde*, vol. 29, p. 33, 1909.

with two different current resistances and calculating the value for the watts when R = O. For instance, in testing a piece of gutta percha-covered wire 7·3 metres long at 4,000 volts the following results were obtained :—

Current Resistance.	Deflection.	Calculated Watts.
200,000	21·15	0·370
100,000	8·97	0·314
50,000	4·04	0·283

Taking the difference between the first 2-watt values, 0·056, and subtracting it from 0·314 a value 0·258 is obtained for the value when R = O. Taking the difference between the values 0·314 and 0·283, and substracting it from 0·283, the value of 0·252 is found for the value when R = O, which is sufficiently near the value found from the first two numbers. In this case the power factor was 4·7 per cent., and the effect naturally increases as the power factor diminishes.

Error due to Potential Divider.—A third source of error in an electrostatic wattmeter is caused by using a high resistance to act as a potential divider for the wattmeter needle. The needle, when at a large potential difference from the quadrants, takes a considerable capacity current. If this is at all comparable with the current flowing in the potential divider, an error arises in a manner similar to those described above, due partly to the phase change of the needle potential when its capacity current has to traverse a high resistance.

If the transformer has its high-tension winding divided into sections, the needle may with advantage be connected to the junction of two of these sections. As the copper winding of the transformer has a comparatively small resistance, this error becomes negligible. For instance, when testing insulating material at 10,000 volts with a power factor of about 10 per cent., the watt reading, when the needle was connected to the middle of the transformer, was 14·1 per cent. greater than when connected to the middle of a resistance of 1·8 Ω. When the resistance was reduced to 0·8 Ω, the difference was 6·3 per cent.

There is, included in this error, the effect of the capacity current in the dividing resistance, due to the fact that a considerable portion of it is at a high potential compared with surrounding objects. The error from both sources can be reduced by increasing the current in the potential divider, but the more convenient method of connecting the needle to the middle point of the transformer has been adopted in the tests described in the paper.

ADDENDUM.

Since writing the paper the experiments on rubber tubing mentioned on page 38 have been continued. Those experiments, in which a direct-current voltage was superposed on the alternating current, indicated a great reduction in the resistance to continuous current when the rubber was subjected to alternating stress; but the continuous current fell to zero when the alternating voltage was removed.

The same red rubber tubing was hung up in the air to dry for a period of ten weeks, the previous soaking period during which the experiments were made being about fourteen days.

It was found on recommencing the experiments that the material had nearly attained its original condition, the power absorbed being 0·7 watt at 6,000 volts and 1·8 at 8,000 volts.

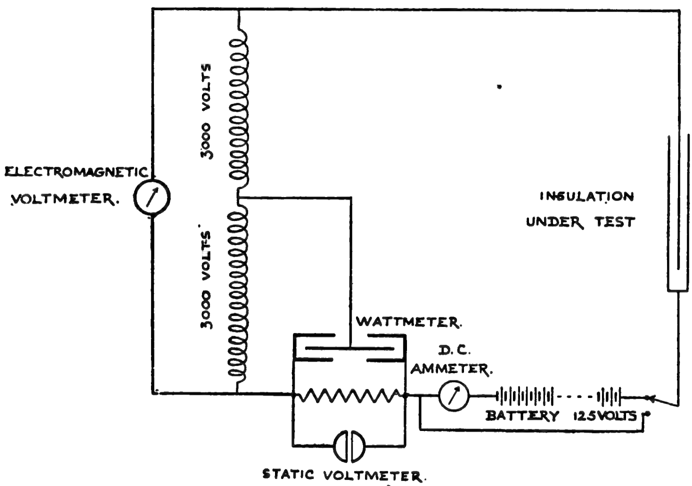

FIG. 26.

For these experiments an insulated battery was used, and a diagram of the connections is given in Fig. 26. The direct-current voltage generally employed was 125, but for great increases in conductivity this was considerably reduced.

From the direct-current voltage and the observed current the apparent direct-current resistance may be calculated; and in order to see how this compares with the results of the alternating-current observations, values for the power loss have been calculated when a potential equal to the alternating voltage used in the experiment is applied to a circuit of such a resistance. This quantity has been termed "direct-current" watts in the diagrams and is equal

to (alternating voltage)² × continuous current/continuous voltage. Fig. 27 gives a typical result showing the rate of increase of the volt-amperes, watts, and power factor, and of the "direct-current" watts. It will be noted that the watts are small initially in comparison with the volt-amperes, most of the current being capacity current; and that the direct-current conductivity would only account for a small portion of the watts measured by the wattmeter.

The power loss increases rapidly as time goes on, and the "direct-

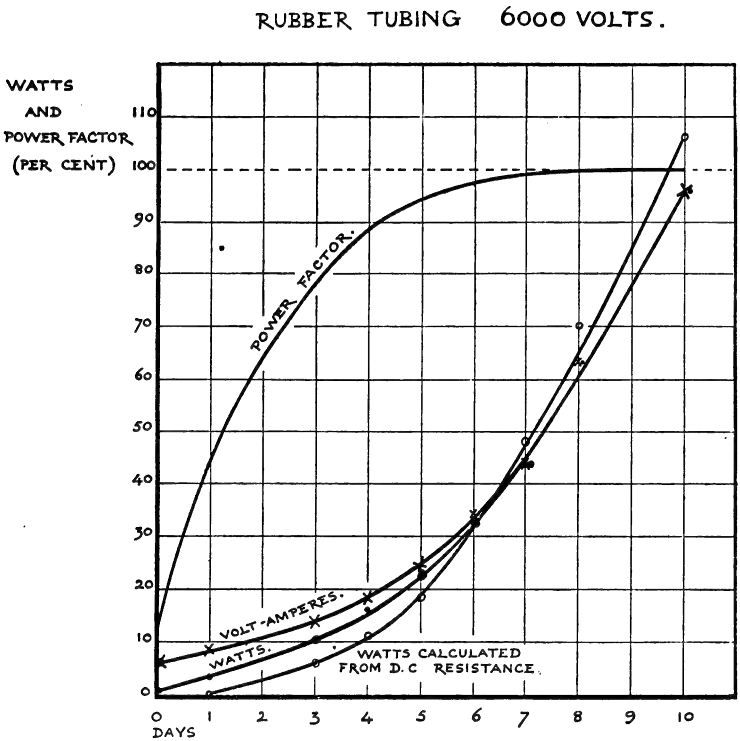

FIG. 27.

current" watt curve rises still more steeply, and is shown crossing the true watt curve. Whether this is actually true is doubtful as the measured direct-current current is superposed on an alternating current of fifty or more times its value, and it is impossible to say whether the latter has no effect on the instrument, in addition to violent vibration of the needle. The watt curve in about a week agrees with the volt-ampere curve, the power factor rising to unity. This increase in alternating-current watts and direct-current conductivity has been

observed to continue for over a month (Fig. 28). The maximum voltage used has been reduced as time went on, some 30 watts being the limit allowed on the length of tubing used, which was about 50 cm., the external diameter being 1 cm. and the material 1·2 mm. thick. (Results of experiments on the 55th and 106th days show that the effect is still increasing.)

At the end of these experiments the insulation resistance at 100 volts direct current was above 200 megohms.

It was thought possible from these experiments that there was some

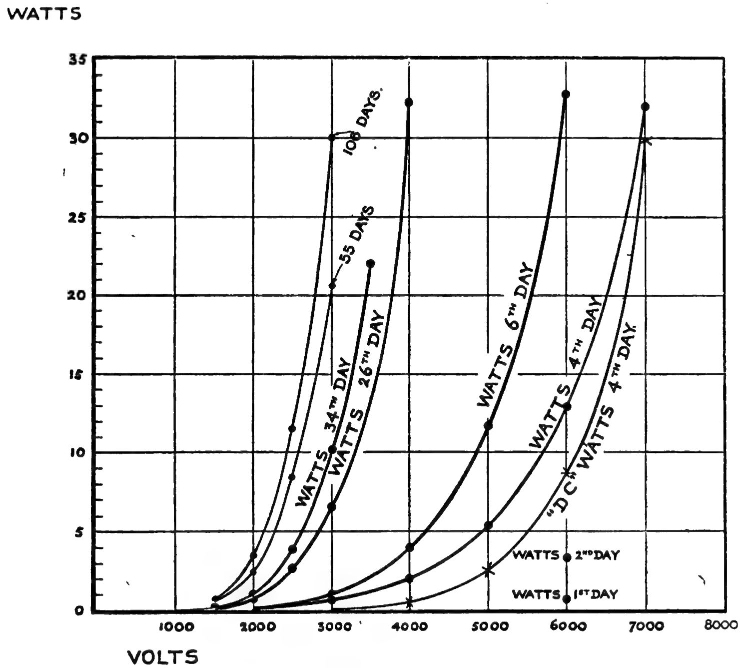

FIG. 28.

direct-current polarisation, and Fig. 29 shows the result of reversing the direct-current voltage at intervals of a few minutes.

It will be noted that the effect is considerable, the "direct-current" watt curve rising instantly on reversal and falling slowly. Moreover the fall goes on for several minutes. It is interesting to see how the true watts follow the polarisation curve, indicating important physical properties of the material in this condition.

Westinghouse Paper Tubing (Fig. 30).—Similar experiments have been done on the sample which was used for the experiments A to Y (Figs. 17 to 22). The voltage between internal mercury and external tinfoil was 4,500 at 50 ∿, and the oven temperature was 23°.

The fan was not running so quickly as in the previous experiments, which allowed the sudden rise in watts to take place sooner, at 70 minutes. The volt-ampere, watt, and "direct-current" watt curve are shown, and it will be seen that the direct-current conductivity accounts for but a small portion of the power loss at the beginning of the experiment; and that there is a nearly constant difference of about 3·7 watts between the alternating-current and "direct-current" watt curves. The power factor rose from 34 per cent. to 57 per cent. during the experiment, and the thermometer in the central tube from 23°

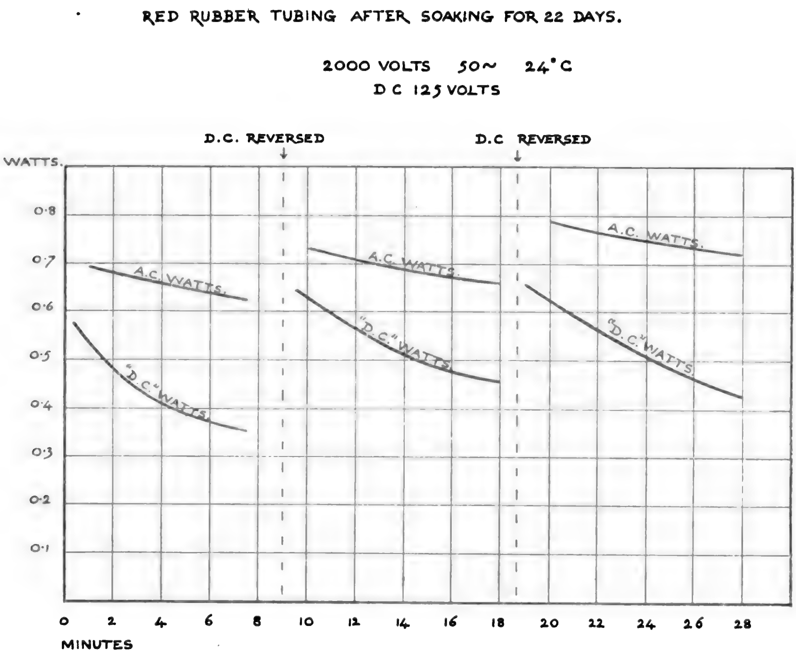

FIG. 29.

to 48°. There seemed to be little, if any, polarisation effect on reversing the direct-current battery.

Oiled Cloth.—Seven layers were wound on a brass tube, forming a cylinder of insulation 34·5 cm. long and 6·5 cm. in circumference. A thermometer was placed in a cork fixed in the top of the tube.

A layer of tinfoil formed the outer conductor. The result of a run at 3,750 volts is shown in Fig. 31. The tube was hung vertically in the oven at 8° C. The fan was kept running for the first half-hour of the experiment, and the power loss rose from 1·9 to 2·9 watts, reaching a steady state. The watts calculated from the direct-current conductivity were very small. At 30 minutes the fan was stopped and

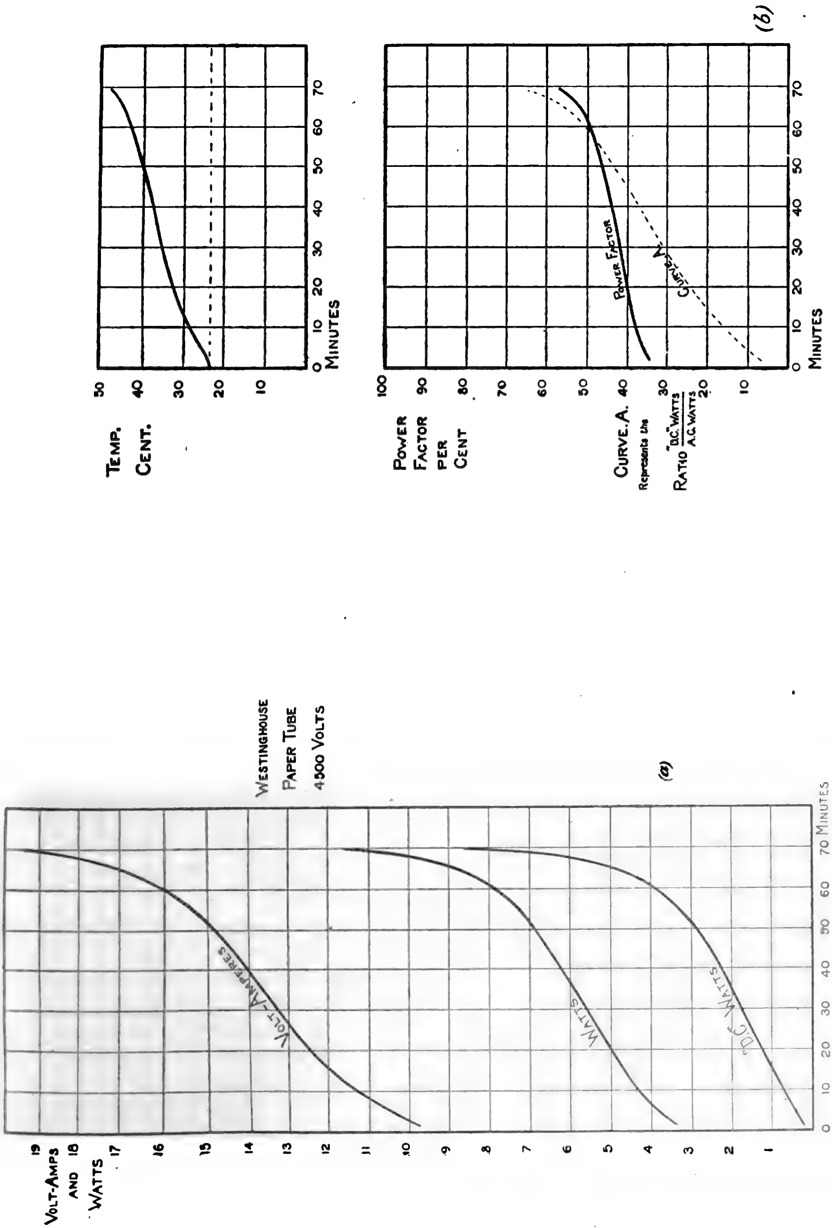
(a)
Westinghouse
Paper Tube
4500 Volts
Volt-Amps
and
Watts
Volt-Amperes
Watts
"D.C." Watts
70 Minutes
(b)
Temp.
Cent.
Minutes
Power
Factor
per
Cent
Power Factor
Curve A
Curve. A.
Represents the
Ratio "D.C." Watts / A.C. Watts
Minutes

FIG. 30.

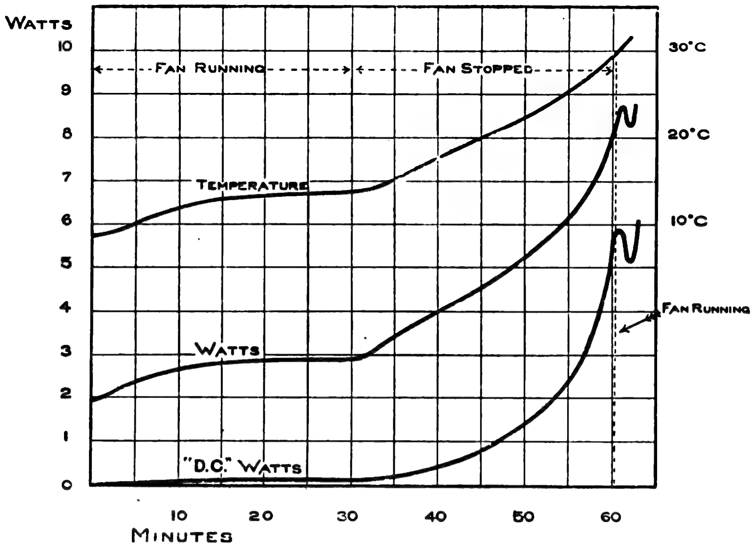

FIG. 31.—Oiled Cloth, 7 Layers, 3,750 Volts.

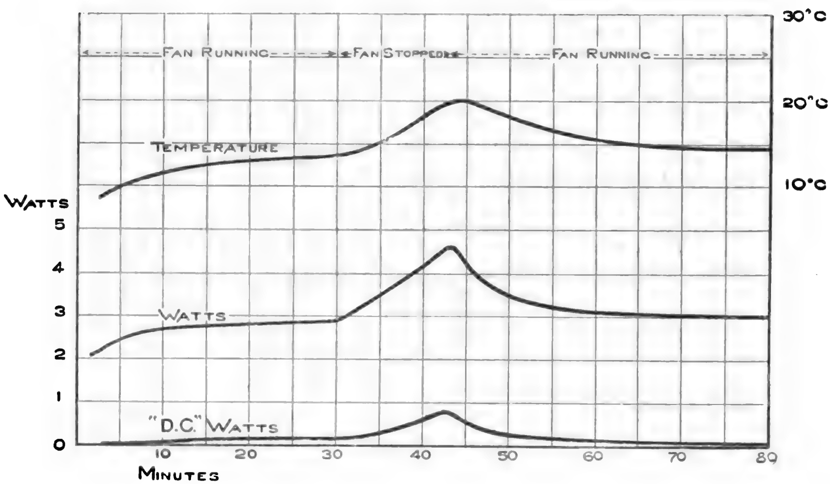

FIG. 32.—Oiled Cloth, 7 Layers, 3,750 Volts.

the less efficient cooling allowed the temperature and watts to rise with increasing rapidity. At 61 minutes the fan was again started with the idea of reversing the slope of the curves; but though for a few minutes this took place matters had gone too far, and the experiment was stopped as the power loss commenced to rise again rapidly.

In Fig. 32 is shown the result of a second run under exactly the same conditions; but in this case the fan was started when the watts had reached 4·5. The various curves follow exactly the course which would be expected from the previous experiment, and afford an excellent example of the information obtainable by these methods of research.

An important difference between the behaviour of this material and the indiarubber is that when the alternating stress was removed from the oiled cloth as soon as the power reached 10 watts, the direct-current measurements showed a conductivity a few seconds later of about $\frac{1}{10}$ of its previous value; whereas in the case of the rubber no conductivity to direct-current could be detected with the apparatus employed, when the conductivity under the alternating-current stress had been considerably greater than in the case of the experiment on oiled cloth.

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The first section includes papers dealing with theory and experiments of a laboratory nature.

The second deals with instruments, chiefly electrostatic voltmeters and wattmeters, suitable for measurements on high-voltage circuits.

The third section includes papers on atmospheric phenomena at high voltages at or above ordinary pressures, more especially such as describe experiments of engineering interest.

In the fourth section are references to similar experiments on oils.

The fifth section consists chiefly of papers dealing with the electric strength of materials and energy loss in insulation. Articles on cables are included which discuss insulation problems; but such as deal merely with capacity, inductance, etc., have been omitted.

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DISCUSSION.

Mr. MILES WALKER: The author's results are exceedingly valuable and cover more ground than the tests of previous experimenters, whilst corroborating entirely the curves that have been obtained before on insulating materials. I take it that one of the main objects of the paper was to find out whether it is better to apply an exceedingly high-voltage test to an electrical machine for a short period or to apply a more moderate voltage for a longer time. The answer to that question really depends upon theoretical considerations and upon some very important practical points. First, as to the theoretical considerations: Consider a cubic centimetre of dry treated rope paper subjected to a pressure of 25,000 volts per centimetre of thickness at a frequency of 50 ∿. The losses in it, measured at different temperatures, might be Mr. Walker.

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found to have the values given by the curve B in Fig. A. The actual watts per cubic centimetre will depend upon the dryness of the specimen, and they will increase rapidly with the temperature. At 20,000 volts per centimetre the losses would be given by the curve A and at 30,000 by curve C. Now the question as to whether in any given test the temperature would settle down to a steady value or continue to rise until a breakdown occurred depends upon the cooling conditions to which the specimen was subjected. Let the line D D′ represent the cooling

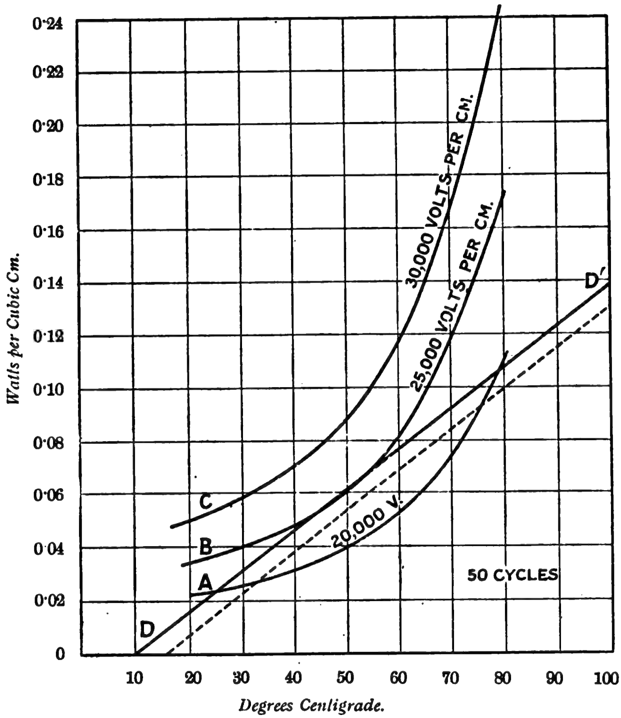

Fig. A.—Watts Lost in Well-dried Rope Paper treated with Sterling Varnish.

conditions in a particular case. The temperature of the surroundings is 10° C. and a rise of 90° (that is, to 100° C.) causes a dissipation of heat at the rate of 0·14 watt per cubic centimetre of material, and a smaller rise gives a proportionate dissipation of heat. With these cooling conditions it is clear that however long the specimen might be subjected to a voltage of 20,000 per centimetre, the temperature would not rise above 25° C., because at that temperature the rate of loss of heat is equal to the rate of gain. (See the 4,000-volt curve, Fig. 17, in the paper.) If, however, the voltage is raised to 30,000 per centimetre the rate of generation of heat is at all temperatures much greater than the

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rate of dissipation, and the temperature will rapidly rise until a breakdown occurs. (See the 5,000-volt curves, Fig. 17.) The rise of temperature will be very quick after 75° C. was reached. Now it will be seen that the line D D′ is drawn as a tangent to the 25,000-volt curve shown, so that if 25,000 volts per centimetre is applied to the specimen the temperature rise will gradually creep up to 50° C. The slightest increase in the loss per cubic centimetre (as, for instance, by an increase in the frequency), or the slightest interference with the cooling (as where the temperature of the surroundings is increased to 16° C., see dotted line) will cause the temperature to increase beyond 50° C. and to rise rapidly until the breakdown occurs. (See the 4,500-volt curves, Fig. 18.) Even at the voltage of 20,000 a breakdown is inevitable if ever the temperature should rise above 80° C., because above that temperature the heat generated is always greater than the heat dissipated. These, then, are the laws which control the rise in temperature, so that no one can say what voltage insulation would withstand unless they know the cooling conditions. It is clear, however, that in fixing upon any test we must see that the voltage curve A, B, or C is not so far above the cooling curve that the state of rapid heating is reached during the progress of test. In practice it will be found that the test voltage usually applied gives a loss curve which lies well below the cooling line. A test of a few seconds is unsatisfactory, because the time cannot be conveniently measured, and the results obtained will be inconsistent with one another. A test of one minute appears to be about right, because the time is long enough to be measured accurately, and very high voltages (say, twice the working voltage) may be applied safely for one minute. If, on the other hand, it is decided to have a long test and the voltage is lowered so as to get more stable conditions, a practical difficulty arises. The electrical manufacturer really applies his test for the purpose of finding out whether the machine is good enough to run under operating conditions. There are two main things to guard against: viz., dampness in the machine, and injury to the insulation during construction. The test the manufacturer wishes to apply is one which will show if the insulation is cracked. If there is a small amount of dampness in the machine he does not want to break the insulation down, as this would necessitate re-winding the generator. If we have damp insulation and apply a moderate voltage (higher than normal) for a long time, we might heat up the insulation until the critical condition is reached, when the breakdown occurs. That is not wanted. If the insulation is broken for three-quarters of the way through, and there is still some insulation left, a moderate voltage applied for a long time might not break through the thin insulation (assuming, of course, that it is dry). If, however, a very high voltage for a very short time is applied, then there will be a brush discharge from the surface where the insulation is broken, and the insulation will break down. For that reason a high voltage for a short time is very much more effective in getting at the fault which the manufacturer wishes to find, but it should not be too short a time.

Dr. Fleming.

Dr. J. A. Fleming: I find some difficulty in discussing many points in the author's paper as fully as I could wish, without anticipating some of the results contained in a paper already communicated to the Institution by myself and Mr. Dyke, which although not covering the same ground, will probably be found to contain explanations of some of the author's observations. One thing is certain: that it is impossible to understand the phenomena of dielectrics without admitting the existence of two distinct conductivities. One of these may be called the conductivity for alternating currents, and is something quite different from the reciprocal of the direct-current resistance measured in the usual manner. The alternating-current resistance, however, involves a true dissipation of energy, much greater than that connected with an equal direct-current voltage. This alternating-current conductivity is a function of the temperature and frequency and is immensely increased by moisture in the dielectric. Hence most thorough desiccation of an insulator is necessary if the energy waste in it under alternating currents is to be kept low. I do not wish to anticipate what I hope to be able to tell the Institution on another occasion, but most interesting facts have been discovered with regard to gutta percha and vulcanised indiarubber. Many of the author's results could be explained by the observation that the increase of energy dissipation under constant alternating voltage tends to increase itself owing to the rise of temperature until failure occurs at some point. I believe there is no subject which can be more fruitfully worked upon at present than the conductivity and properties of dielectrics, for since the energy is conveyed through the dielectric we ought to know as much about the nature of dielectric conduction and energy dissipation as we do in the case of conductors. As regards the effect of immersion of dielectrics in oil, I should like to know from the author whether he recommends oil insulation for ordinary transformers or not. In the case of transformers used in wireless telegraphy, oil insulation is necessary to prevent internal brush discharges and consequent failure of transformers, as was discovered in the early days of large wireless telegraph stations. Whether it is equally necessary for ordinary lighting transformers does not seem quite certain, as some makers recommend oil insulation and others advise against it. It has at least the merit of keeping down brush discharges and preserving the dielectric from damp.

Mr. Everest.

Mr. A. R. Everest: In connection with the question of injury to insulating materials by prolonged high-tension tests, the information contained in the first part of the author's paper may be studied under three heads: (1) The question of endurance—*i.e.*, relation of test voltage to length of time to produce a breakdown. (2) Conditions which produce fatigue—*i.e.*, the temporary weakening of the material. (3) Conditions which produce permanent injury—*i.e.*, permanent reduction in insulation strength: we have also the effect of temperature as modifying all these conditions. Regarding the question of endurance, it may be of interest to mention some tests made

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upon varnished cloth to determine how much greater potential could be endured for very brief applications as compared with the usual test lasting 10 to 15 seconds. The tests were made with a swinging pendulum contact sweeping over a contact plate, the pendulum being raised to various heights to give various times of contact. For each length of time a large number of tests were made, the voltage being varied until a voltage was found at which 50 per cent. of the samples punctured and 50 per cent. did not. This was taken as the critical voltage for that time of application. The general results show that, taking as unity the potential required to break down the material in 15 seconds, 20 per cent. higher potential could be endured for half a second or 60 per cent. higher pressure for $\frac{1}{10}$ second. It is interesting to note the confirmation of these results in the author's Table E, where the voltage to puncture in "0" seconds (presumably the small fraction of a second) is 66 per cent. higher than that needed to puncture in 14 seconds. These facts emphasise the necessity for having a recognised length of application for breakdown tests, or rather that the breakdown strength, when expressed as the result of test, shall always be understood as applying to a test of specific duration. The time selected by the author, 10 to 15 seconds, is a very convenient standard as the ultimate strength varies little over this range. Some very interesting figures illustrating fatigue and recovery are shown particularly in Table K, where fresh material broke down at a certain voltage in something over 10 seconds, but if previously subjected to 1 minute at 80 per cent. of that voltage its endurance for the full test voltage was reduced to one-quarter of its full time if no rest intervened; but increasing the periods of rest the endurance increased until after a minute's rest its original endurance was restored. While obviously more difficult to determine, it would be of great interest to know how the relations would stand if instead of varying the time of application the voltage itself had been varied till the voltage was determined, in each instance, which would produce puncture in the initial time of 10 to 15 seconds. A particularly interesting test is that in Table L, showing the effect of permanent injury. The results are expressed in varying time of breakdown at a given voltage. From endurance curves available the equivalent voltage which should be needed in each case to produce a breakdown in 15 seconds has been estimated at 12,000 volts for the fresh material, while that subjected to 5,000 volts for 2 hours, followed by an all-night rest, had an ultimate strength of about 6,000 volts, that is to say, its ultimate strength was weakened 50 per cent. by its previous subjection for 2 hours to 40 per cent. of its natural breakdown voltage. Table Q gives further interesting illustrations confirming, as the author points out, the permanently injurious effects of long time test application. The author also points out how chilling, produced by the electrode, may retard puncture and shows the effect of using tin-foil covered knobs instead of metal knobs. Another good illustration of this point is found when testing slot tubes. If a steel

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mandrel is used as the internal electrode, unduly high puncture values are obtained due to the chilling effect of the mandrel, which retards the breakdown of possible weak spots. The author has pointed out the destructiveness of corona or brush discharge, and this is itself another important argument against long time tests. This recalls the case of a micrometer spark-gap in a glass-enclosing case which would persistently discharge after being alive for half an hour at about one-third the voltage normally required to strike across the gap setting. This would not occur if the glass case were open so that it was ventilated. A similar occurrence may take place if a long time test is applied to a large alternator at standstill. The spaces around the windings fill with electrified air which is conducting, thus cutting out the safety factor provided in operation by the large air-spaces. Damage to the coil insulation can readily occur by local heating from the electrostatic discharges which become excessive when this stage is reached. In some cases where long time tests have been insisted upon it has been found advisable artificially to ventilate the machine by allowing it to revolve slowly or by other means in order to avoid this unnatural condition. On page 20 reference is made to tests on composite insulation consisting of varnished material between mica plates, and the author points out that the varnished material may be destroyed without puncturing the mica. In the "Conclusions" he refers to this as "Destruction by Charring." Will the author kindly say whether he has examined the material for evidence of minute punctures? In some similar tests it was claimed that microscopic examination revealed actual punctures caused by the capacity current.

Dr. Russell.

Dr. A. RUSSELL: In the author's experiments the electric stresses round the electrodes before the disruptive discharge occurs are enormous, and hence the air round them has broken down and become a conductor. Under these circumstances the shape of the electrodes is practically immaterial. The electrostatic attraction between the spherical electrodes which were used must have been appreciable as the sheets of mica were extremely thin. For instance, in one of the experiments the distance between the 2-in. spheres used was the two-hundredth part of a centimetre and the potential difference between them was 10,000 volts. If they had been in a vacuum the attraction would have been greater than the weight of 283 grammes; how much greater depends on the value of the dielectric coefficient of the mica. In the experiment, however, there was a quantity of ionized air between the electrodes and the mica, and this broken-down air has a very high dielectric coefficient. Hence the attraction between them would be much larger than the figure given above. Experiment proves that the temperature of the boundary of the corona is the highest. The puncture of the mica, therefore, takes place at this boundary. The author says that when we put mica in oil its electric strength is much reduced. In my opinion the real electric strength is a true physical constant. It is always the same at the

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same temperature and pressure. It would be interesting to test the mica sheets in carbon dioxide or in an inert gas, like nitrogen, or in a very perfect vacuum as the results would probably give us a further insight into the mechanism of the discharge. It might even enable us to estimate the true electric strength of mica. The author only gives us its apparent electric strength. This is of practical value, but I confess to a feeling of disappointment. The experiments described in the later part of the paper are of great interest. The discovery that the ohmic resistance of indiarubber is very small when it is subjected to high electrostatic stresses is quite novel to me, and seems of importance. Professor Fleming has apparently made the same or a similar discovery. The "insulation resistance" measured when testing a cable is not a true resistance. Amongst other things, its value depends on the time during which the testing pressure is applied and on the absolute value of this testing pressure. My experience with direct-current tests is that the higher the pressure the greater is the apparent value of this "insulation resistance." Before drawing any conclusion from this, however, it is necessary to consider very carefully what it is that we actually measure.

Mr. Addenbrooke.

Mr. G. L. ADDENBROOKE: It may be useful, perhaps, if I point out some variations of Mr. Rayner's tests which I think are of practical importance, especially with regard to the points that Mr. Miles Walker has mentioned. I will try briefly to illustrate this point which is common to both classes of insulation. I found after a good deal of experimenting, first of all by raising the voltages step by step and measuring the watts last, and alternatively by raising the pressure to a fairly high point for a certain time, keeping the pressure on and observing the result, that what appeared to be the best test for practical purposes was a sort of mixture between the two, and one which I think enables the point that Mr. Miles Walker made to be dealt with effectually. To carry out this method, when I was about to experiment on a material by a preliminary test and raising the pressure quickly and keeping it on only a very short time, I found out approximately what pressure it would break down at. If then we apply, say, one-third of this pressure to start with we will get a certain watt reading which I took as a basis for calculating the power factor. After getting this watt reading I then immediately raised the voltage to, say, double the pressure. Then if we observe the wattmeter we will find that if it is the first reading the second reading will be somewhat more in proportion than the relation of the square of the two pressures. If the pressure is still below what I call the first critical point, the heating of the material establishes a heat slope in it from the inside to the outside. When the steepness of that heat slope balances the extra loss we again get a stable state, and if we keep the pressure on for a very long time nothing more will result. If now we raise the voltage again and keep the wattmeter on we will find a bigger difference, and an experienced operator can soon judge by putting on not much more than two-thirds of the breaking-down voltage what is going to happen, and we can then leave

Mr. Addenbrooke. the current on for a time and watch the actions taking place. This is the point about the commencement of Mr. Miles Walker's curve, where the dissipation of energy no longer becomes as great as the generation of energy, due apparently to the fact that the hotter the material gets the better conductor it becomes and the greater the loss in watts. There is an alternating-current temperature coefficient. I have got this out for a number of materials, and it is an interesting point that in good insulators the coefficients are entirely different from the temperature coefficients obtained with continuous pressures. It is a very interesting physical fact that a material may have two temperature coefficients. An experienced operator can very easily work on these lines until he gets to a point, which I call the second critical point, where the curve begins to turn up rapidly. We have in this way the whole thing so much in our hands that we can easily judge the quality of the insulation. Then a very important point arises—the question of how far we can proceed up this curve past the second critical point without damaging the insulation, and what happens to this energy. The watts are expended in the dielectric, and some are undoubtedly dissipated as heat. The question is, is all the energy dissipated in heat or are chemical changes produced? It is quite possible that in some cases chemical changes are produced, but I think in the majority of materials used by engineers in insulating work there is very little chemical change, or scarcely any at all. What really happens is that the energy lost is dissipated in heat, and if we do not heat our materials up to a point which will cause chemical changes to take place we can turn round the corner of the curve to what I call the secondary point, and if we do not put our pressure up too quickly we can carry up the pressure almost to the breakdown point, and cut it off without damage. This enables us to examine materials which have been stressed nearly up to the breakdown point. If insulating materials so stressed are allowed to cool thoroughly, as a rule I think there is not much damage, and that is very satisfactory. At any rate, a comparatively short application of these high voltages, as far as I have been able to make out, does not do much damage to the insulation, if not carried too far. Of course if we do not let the insulation cool and then put on the high pressure again, it will go. I have made some tests on insulating materials which were allowed to cool, and I found that if we can get them back into the same state as they were in to start with there is no doubt that a second curve of watt losses will agree closely with what it was before. It is very satisfactory to find that Mr. Rayner is using the formula for his wattmeter which is practically the same as I gave with Dr. Russell's help ten years ago, and that with the long experience of wattmeters at the National Physical Laboratory they have not found any reason for altering it. There is one other point that I should like to mention with regard to what Mr. Rayner says as to the question of theory. It is very important to get a right theory in this class of work, otherwise it gets so utterly confusing. Mr. Rayner has quoted 250 different papers here. I have read a

good many of them, but there are three or four times that number which could be quoted, all written from disconnected standpoints, and it is very difficult to bring them together. Some time ago I came to a conclusion something like Mr. Rayner's as to the nature of the actions occurring. If the actions are of the character suggested by Mr. Rayner, it should be possible by means of the wattmeter by certain measurements to test this theory experimentally. I have made those tests, but the results do not agree with the theory. Since then I have worked on the question of the effect of periodicity on these losses. I have gone down to periodicities as low as 1 period in 5 seconds, and it is there we begin to see where the real changes and connections lie. If the theory of the thing were what Mr. Rayner tentatively suggests, it is possible, I believe, to predict what the behaviour of the insulator should be at a certain voltage over a large range of periodicity. I have tried that. I worked theoretically backwards to that, and then I worked forwards by actually making the tests, but they do not agree. It is an altogether different action, and I think undoubtedly the action is on the lines that Dr. Fleming has suggested. Unless we come to the electron hypothesis all the old theories are hopeless. While I do not want to say that this is right, it at any rate gives us some connected and helpful basis to work on. **Mr. Addenbrooke.**

Mr. P. R. FRIEDLAENDER (*communicated*): During the last two years I have been experimenting on somewhat similar lines to the author's, more especially with a view to comparing the effects of direct-current and alternating-current voltages applied to various kinds of fibrous insulation materials. I have used an Addenbrooke electrostatic wattmeter, suitable for 1,000 volts, connected either to a small 1,000-volt direct-current dynamo or to one-tenth of a 10,000-volt transformer. The direct-current results have also, in many cases, been checked by galvanometer readings. One of the most characteristic results brought out by these tests is the marked falling-off of the insulation resistance as the voltage is raised—a point mentioned by the author in connection with tests on rubber tubing at the end of his paper. The fact that insulators do not follow Ohm's law but vary their resistance with the voltage used for the measurement has long been known, but the remarkable regularity of the variation and its important effect on the breakdown point do not appear to have been recognised. In Fig. B a typical result is given, obtained on a sample of oiled paper $\frac{1}{10}$ mm. thick, tested between 9 sq. in. electrodes of soft rubber covered with tinfoil and loaded to $3\frac{1}{4}$ lbs. per square inch. Curve I. gives the insulation resistance measured with a galvanometer in the ordinary way, and it will be seen that this falls off steadily from about 22 megohms when measured at 15 volts to about $5\frac{1}{2}$ megohms at 600 volts. Curve II. shows the watts lost in the material, calculated from the resistances of curve I., and the circles against curve II. indicate the corresponding results obtained from a subsequent direct measurement of the direct-current watts by the electrostatic wattmeter. Curve III. shows the watts, measured by the wattmeter, when an **Mr. Friedlaender.**

Mr. Friedlaender.

alternating-current voltage of 50 ∿ was used. It will be seen that the alternating-current loss in this particular sample at a given R.M.S. voltage is about three times as great as at the same direct-current voltage. Concordant results are often difficult to obtain, and the actual figures vary considerably from sample to sample of the same material, but, in order to avoid disturbances as far as possible, the above three tests were all taken within the space of a few minutes—

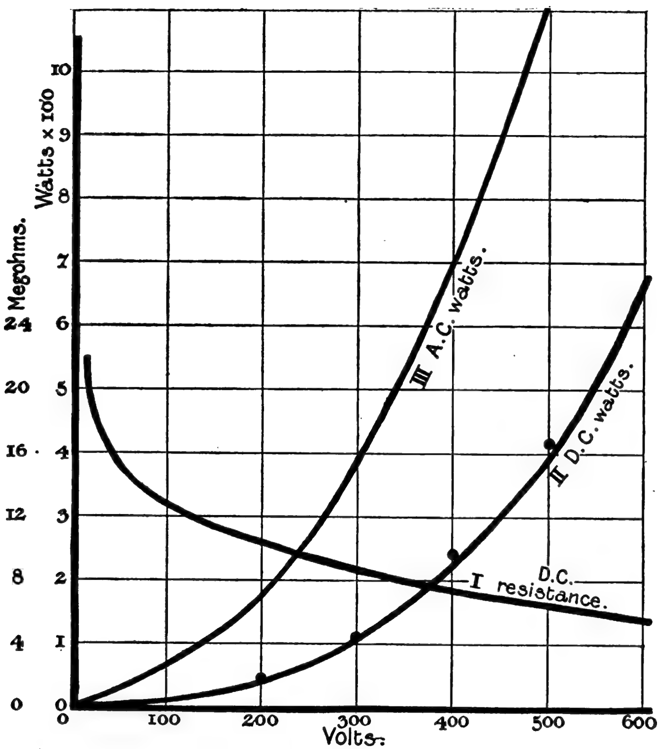

Fig. B.

the alternating-current test being made between the wattmeter and the galvanometer direct-current tests. The voltage was in no case taken sufficiently near to the breakdown voltage (which was about 650 volts alternating-current) to affect the material appreciably. All the materials tested, including press-spahn, leatheroid, various oiled papers and oiled linen, gave similar curves connecting resistance and voltage. The shape of the curves is not unlike that connecting the contact resistance of a carbon brush with the current passing, or that connecting the resistance of an ordinary coherer with the voltage

applied, and in both these cases the temperature rise due to increased current, in combination with a high negative temperature coefficient of resistance, appears to be largely responsible for the effect.* In the case of these insulators the effect may also be partly due to temperature, but this is hardly the sole cause, because if a higher voltage is suddenly reduced to a much lower one, the resistance almost instantly regains the higher value corresponding to the lower voltage. Electrostatic attraction between the electrodes probably also has some effect, because experiment shows that as the weight on the electrodes is increased, the resistance at a given voltage falls steadily, at any rate, until pressures of several pounds per square inch are reached. Whatever the cause of this fall in resistance with increase in voltage, the fall is pronounced enough to make the actual C^2R losses at or about the breakdown voltage a very important factor in producing the breakdown. The final breakdown may, in fact, be considered as being simply due to the actual charring, through excessive C^2R loss of the one or two weak spots which carry most of the current. Some of the author's later results seem to show that even with alternating-current tests the C^2R losses form the greater part of the total losses at the instant of breakdown. Mr. Friedlaender.

Mr. A. CAMPBELL (*communicated*): Among the author's many interesting results there is one which is particularly novel. He finds, for a given voltage, that in gutta percha the power loss increases as the temperature is lowered. In standard mica condensers the power loss due to absorption decreases as the temperature is lowered. It is very interesting to find a material largely used in practical work which behaves in the opposite way. This discovery may help to throw light on the difficult subject of dielectric absorption, which is of practical importance in connection with the effective leakance of telephone cables. Mr. Campbell.

Mr. E. A. WATSON (*communicated*): There are two points which I should like to raise in connection with the author's paper. In the first place he has proved that if an insulating material is severely tested while immersed in a material which is electrically weaker than itself, it is liable to be damaged by heating and brush discharge, the change in the nature of the insulation being chiefly, I take it, a chemical one. This is the most common case as generally met with in ordinary high-tension work. There is, however, the converse case in which an insulation is immersed in a material electrically as strong or stronger than itself, as, for example, ebonite immersed in good insulating oil or highly compressed air. My experience is that in this case also there is a liability to permanent injury if the voltage applied is too high, even although actual breakdown does not occur. This is especially the case if there are any sharp edges present on the conducting surfaces which are in contact with the insulation, but the nature of the injury is rather Mr. Watson.

* See Arnold and Pfiffner, *Elektrotechnische Zeitschrift*, vol. 28, p. 263, 1907; or *Science Abstracts*, vol. 10, B, No. 398, 1907; and Eccles, *Philosophical Magazine*, vol. 19, p. 869, 1910.

Mr. Watson. different, and is, I believe, chiefly if not wholly mechanical. If a piece of plate glass be taken and placed between a pair of point electrodes or a point electrode and a plate and then submit it to a high alternating or intermittent potential (such as is given by an induction coil) just not sufficient to puncture it immediately, it will be found on examination under a microscope to be traversed by a number of fine, hair-like incipient punctures, which do not completely pierce the plate, but which, starting from the outside, gradually thin out and get lost in the interior. If the period of application of the potential be increased these lines grow and extend until a puncture occurs. This can be brought out very strikingly if a spark-gap shunted by a capacity be arranged in parallel with the testing apparatus so as to set up high-frequency oscillations and subject the specimen to a large number of electrical impacts in a short period of time. It is then possible, with a voltage well below the ordinary breakdown value of the material, to produce etchings and markings in it which are plainly visible to the naked eye. There is a great deal of experimenting which might be done in this direction, but I think there is little doubt that if certain classes of insulation are too severely tested, incipient punctures may be started which will decidedly weaken the material and make it less able to stand severe electrical stress. The second point to which I would refer is in connection with the electrostatic wattmeter. I presume that the instrument has to be used with a torsion head in a similar manner to a Siemens dynamometer. Otherwise it seems to me that there might be very serious errors produced by any slight differences in the dimensions of the two quadrants. I should be glad if the author could make this point clear, as some time ago I intended to construct a high-tension electrostatic wattmeter working in compressed air but gave it up on this account. If it could be made direct reading it would, I am sure, be a very useful instrument indeed.

Mr. Fleming. Mr. A. P. M. Fleming (*communicated*): From the author's experiments on oiled fabrics he draws the conclusion that the effect of a long application of a pressure test is very generally more deleterious than that of a short application of a higher pressure. This has been clearly demonstrated with tests made on only a few sheets of material. He shows that the deterioration is mainly due to brush discharge acting on the outer surfaces of the material, and, as is to be expected, the difference becomes less and less marked as a decreasing number of sheets are used. It would be interesting to have the test results shown in Table Q supplemented by watt-loss curves similar to those shown in Figs. 13 and 14, where the pressure has been applied long enough to push the curve beyond the knee on to the upward bend, *i.e.*, beyond the point at which permanent damage due to internal charring presumably occurs, and yet not so far as to cause actual breakdown. Such tests would have been of considerable value in determining more conclusively the relative danger of short- and long-time tests, since in actual practice for all but very low voltages the thickness of material

used is very much greater than that employed in the earlier tests mentioned in the paper. For this greater thickness the deterioration due to brush discharge on the outer layers, even for long-continued pressure tests, will be negligible. From results obtained in practice on high-voltage armature coils it has been found possible, even with very short-time tests, of the order of, say, 30 seconds, to stop the test after permanent deterioration has occurred, but before actual disruption has taken place. Such results were obtained on a 6,000-volt stator winding, complete breakdown curves for which have been set forth in an article by Mr. R. Johnson and myself,* and incidentally these tests show what a large factor of safety is provided in high-voltage machines as far as the insulation between windings and ground is concerned. While, therefore, when flaws or weak spots exist, some danger of causing permanent deterioration under test, due to internal heating, may occur, the ratio of the breakdown pressure to the testing pressure is so very much greater than that in the author's tests that there is much less likelihood of even surface deterioration due to brush discharge. A further point of importance in connection with the application of the author's conclusion to commercial testing is that in the case of machine windings, where mica is usually largely employed, although the supporting organic materials, such as paper and fabrics and cements, employed may be permanently damaged under test, the mica which affords the major portion of the insulation would be unaffected. From other considerations the short-time high-pressure test is more usual in commercial testing than a lower voltage applied for a long time, since it tests more effectively the surface insulation, and, further, is more convenient to apply, this being of considerable importance to manufacturers where many tests have to be applied daily. At the same time, it is well to keep in mind that the main function of a pressure test is to detect flaws or mechanical damage in the insulation and to determine whether a sufficient thickness of insulation is used, but it affords very little guarantee as to the reliability of the apparatus. Referring to the latter portion of the paper, it would be interesting to know whether the author has arranged any watt-loss curves when the test specimens were immersed in oil or placed in a medium of compressed air in order to eliminate as completely as possible the loss due to brush discharge. Mr. Fleming.

Mr. W. E. Burnand (*communicated*): The figures given by the author show a much greater effect due to small variations in temperatures and applied pressures than I should have thought would be the case. The reason for this, I think, is that workshop tests, with which I am chiefly concerned, are usually much further from the "last straw" than the author's, and it is chiefly about this degree of stress that these effects become prominent. The wattmeter tests appear to me to be specially instructive, showing what may be termed the "yield-point" of insulation, this being where the rate of increase of energy input exceeds the rate of increase of energy output or heat dissipation from the insulation, as pointed out by Mr. Miles Walker. Mr. Burnand.

* *Electrical Review*, vol. 69, p. 842, 1911.

Mr. Burnand.

The electrostatic wattmeter, especially on these low powers and low power factors, is hardly a workshop instrument, and I am afraid that in the hands of the average operator the results would be open to so much question as to be of little interest and less value. In the comparison at the top of page 46 there would, of course, be some error, due to the capacity current across the dividing resistance, in addition to the capacity current due to the difference of potential between the resistance and its surroundings, unless the capacity of the resistances themselves was compensated by their being made slightly inductive to balance the capacity at the particular frequency and voltage used in the tests. I notice in curves 9 and 10 that each time the test is interrupted for examination of the material, with the exception of the first point on Fig. 10, the watt loss on the resumption of the test is increased, although the temperature has fallen in the interval. The exception noted I take to be due to the escape of steam. Can the author say if the increases occur without separation of the electrodes? If not, it would appear that something is absorbed or taken up from the air during the separation, but this would hardly be moisture in view of the high temperature of the material. Has the author any explanation to offer? Speaking of insulation research generally, I think that if two separate effects are recognised, and, if possible, separated, it will be a great aid to progress. The two effects are: Those that occur within the body of the material under stress, and those due to the influence of the adjacent media. For instance, mica in air often has its resistance to puncture enormously reduced by, say, a drop of wax near the electrodes, and again, look at the difference between what it will stand in air and under oil! These cases of reduction show the great influence of the nature of the adjacent media since the oil or wax respectively do not penetrate the body of the material. I should expect a great difference in curve 12, with the two effects separated. In view of this separation of surface and internal effects, I feel somewhat disappointed that with the apparatus at the disposal of the author, the pressures have not been carried very much higher, since it is chiefly at these higher pressures that most uncertainty exists, and the order of importance of the several effects that go to make up the resultant may be different to that of lower pressures, but no doubt the author will have something to say about this later on. There is much to be learnt yet about the influence of oil on various fibres—for instance, why manilla, in oil, stands so much better than most other fibres, and a given thickness in oil will stand so much more than the manilla or oil separately. Are we to say that the fibres increase the dielectic strength of the oil, or that the oil increases the dielectric strength of the fibres, or is it merely a mechanical effect? I am inclined to favour the last, and that the effect is due to the rough fibres of manilla preventing displacement of the oil by the advance detachments of electrons, or whatever they may be, that make way for a breakdown. It can hardly be due to increased heat conductivity, since, due to the stoppage of circulation of the oil, this would be less than the oil alone. I was much disappointed some

time ago when testing some Japanese paper with specially long fibres—longer, it appeared to me, than manilla—at the poor results, and I can only account for this by reason of the fibres being smoother than manilla. Mr. Burnand.

Mr. H. D. SYMONS (*communicated*): In testing insulating materials with high voltages it is essential to distinguish between tests for dielectric strength and tests to determine the soundness of insulation. Insulation tests on machinery and apparatus are for the latter purpose, and the author's experiments show the flexibility of such tests. The possibility of varying the voltage and time enables tests to be applied to meet varying conditions, for in cases where it is impossible to apply a high voltage for a short length of time, a lower voltage may be applied for a longer length of time and give an assurance of the soundness of the insulation. Fig. 16 shows that the loss in watts per square centimetre at 6,000 volts after about 35 minutes are the same as the loss at 7,000 volts after 5 minutes. This is of considerable interest, as tending to show that under similar conditions a test of 7,000 volts maintained for 5 minutes would be equivalent to a test of 6,000 volts for 30 minutes. The actual deleterious effect of a prolonged voltage test, however, differs with different dielectrics. The deterioration of a fibrous material such as oiled or varnished cloth under prolonged voltage stress would be far greater than the deterioration of mica. The reasons are that the damage caused by the discharge at the electrode edges is marked in the case of oiled cloth, and also it contains moisture. With electrodes similar to those used by the author—viz., No. 2, Fig. 2—accumulation of moisture on the contact surface frequently occurs during prolonged voltage tests. This rarely occurs with electrodes with small heat capacity unless the material is exceedingly damp. I believe that the damage due to moisture in fibrous materials under prolonged voltage tests is, as a general rule, greater than the damage by surface discharge, and the author's experiments on the effect of desiccation help to support that belief. As an instance of what may be done, I once successfully dried a thick piece of wood that was locally damp, by giving the damp spots a "30,000-volt massage," intermittently applied by suitable electrodes without damage to the wood beyond a slight charring at the damp spots. I would like to ask Mr. Rayner whether he experienced a greater number of breakdowns between the electrodes with the prolonged voltage tests than with the short-time tests, and also the nature of the rupture on the Pertinax tubes. The paper clearly establishes the fact that if the heat during a high-voltage test can be dissipated at a greater rate than it is generated, the probability of a breakdown is slight. It is also interesting to note that the energy loss with mica remained constant under given conditions, whilst with the other materials the increase was marked. This suggests that the energy loss in organic materials is of a different nature to the loss in inorganic materials. Mr. Symons.

Mr. E. H. RAYNER (*in reply*): Mr. Miles Walker's remarks emphasize the importance of cooling conditions on the endurance of insulation Mr. Rayner.

Mr. Rayner. under test on account of the very large temperature coefficient possessed by most insulating materials. The impossibility of giving any specific values for power loss without completely specifying the conditions is exemplified by a comparison of Figs. 7 and 31. In the first, the results of an experiment on four layers of material at 10,000 volts is shown; and in the other, of 3,500 volts on seven layers of the same material. In both cases the temperature conditions determine the safety of the material. The much lower potential stress admissible in the second case is accounted for by the fact that the first experiment was between flat metal plates of considerable heat capacity, and cooling took place from both sides of the insulating material. In the later experiment the material was wrapped on a tube, so that nearly half the heat was prevented from escaping in the same way. The temperature rise thereby caused lowers the permissible electric stress about five-fold. I am glad to find that my opinion gathered from these and other experiments agrees with that of Mr. Walker and other designers, who are in favour of short-time high-voltage tests on electrical insulation.

The paper of Dr. Fleming and Mr. Dyke will be awaited with great interest by all workers on the electrical properties of insulating materials. The experiments described in my paper illustrate the fact that dampness of insulation is of the greatest importance in determining the heating under electric stress, and consequently determines whether failure will ensue or not. There may be distinct danger in applying a pressure test to really satisfactory plant, if built under unfavourable humidity conditions, before it has been dried out by working in service for some time. As regards the immersion of transformers in oil, I should say that such immersion is practically always an advantage and, for transformers above a few thousand volts, a necessity. It prevents brush discharge and increases the sparking voltage between the windings. In addition it helps greatly to cool the more buried windings of the transformer. At the same time, oils which will give excellent results when tested chemically, will not necessarily be equally satisfactory electrically. We have recently tested various samples of oil and, though the water present was but a "trace" chemically, different samples gave very different results when tested by the electrostatic wattmeter. Though not necessarily differing materially in breakdown voltage, I have found that at 8,000 volts between 12 mm. spheres 3 mm. apart in oil, one sample may give a reading on the wattmeter ten times as large as another. In such a case the lower reading was about 0·02 watt. A wattmeter of this type is capable of detecting about 0·001 watt at such a voltage and a sample of insulating oil has been tested which showed less than this power loss when tested under the same conditions.

I agree with Mr. Everest in his finding that comparatively short-time tests on insulating materials generally give the most consistent results, and the time selected, roughly 20 seconds, is about the shortest

compatible with accurate reading of the voltmeter. As regards his suggestion as to modifying the methods used in Table K, the results are so dependent on the cooling conditions that any general deductions from such experiments might be quite misleading. These experiments were carried out with the electrodes shown in Fig. 2, No. 2. The heating which produced the weakening shown in Table K is due to the heating beyond the edge of the metal electrode, where the material is not in contact with the metal. The cooling after switching off the initial voltage is comparatively rapid, as it is not a case of alteration of temperature of a large mass of metal as well. After the initial application, the material between the electrodes has but a small temperature rise, as the large mass of metal quickly abstracts the heat. Just out of contact, where the brush discharge assists in heating the material, is where it always fails. I have noticed the same time effect as that which Mr. Everest mentions with an uncovered spark-gap, although naturally not to the same extent. The sparking voltage across an air-gap depends on the time of application of the voltage, especially when there are no draughts. Mr. Rayner.

As to the suggestion that the scorching of oiled cloths under high electric stress between mica sheets may be associated with minute punctures, I have examined the material, and do not find that in these experiments this has been so. It is interesting to note, however, that the darkening in colour takes place in the region of the threads and not in the interstices, at least to anything like the same extent. It seems probable that moisture is attracted rather by the fibrous material than by the filling.

Dr. Russell mentions a very appreciable electrostatic attraction of some 300 grammes when testing thin mica. The weight of the spherical electrode was about 600 grammes, and care was required not to crush the mica in placing it in position. Interesting results of the effect of corona might be obtained by measuring the electrostatic attraction of two electrodes separated by an air-gap and mica. From experiments on mica condensers the power loss in them is quite negligible, and the measurements in the paper are due to the loss in the air and, to some extent, in the adhesive materials.

I agree with Mr. Addenbrooke that the power losses vary very generally as the square of the voltage, and in many cases it is only the time taken in making the observations, thus allowing temperature conditions to alter, which prevents measurements being obtained that would apparently confirm the law to a high degree of accuracy. The later experiments described in the paper show, however, that when a considerable temperature rise has taken place, and the energy dissipated is considerable, much of the loss is independent of the frequency, and is similar to a direct-current effect. As is especially shown in the case of damp rubber, the loss increases often very much more rapidly than the square of the voltage.

Mr. Friedlaender mentions experiments in which he has measured the apparent resistance of insulating materials under similar alternating

Mr. Rayner. and continuous potentials. In the examples which he gives he finds that the continuous-current resistance so calculated accounts for about one-third of the heating under alternating potentials. My experiments, superposing a continuous potential on an alternating one, show that the ratio is very variable. In the same experiment the continuous effect may be inappreciable at the beginning, but as the material gets warm, the greatly reduced resistance to continuous currents will account for most of the energy wasted.

With regard to Mr. Watson's remarks concerning damage to insulation immersed in oil or compressed air, I have had no experience of the latter condition. My impression is that the large surface required around the electrodes when testing mica, for instance, in air, as compared with that required for the ordinary insulating oiled cloths, is due to the energy-absorbing effect of the surface of the latter by which the power of the spark is considerably quenched. I should not have thought that ebonite would be inferior to compressed air. Good qualities will stand 50,000 volts per millimetre between spheres under oil, though in the thinner sheets a curious preference is often developed for piercing through an adjacent 6 mm. rather than the prepared spot of $\frac{1}{10}$ the thickness. As to the wattmeter, it is not a torsion instrument, but a deflecting one. There is no trouble of the nature which Mr. Watson suggests. The only effect of want of symmetry is to cause a slight shift of zero when the needle is alive, both sets of quadrants being at the same potential. This can easily be reduced to quite an unimportant quantity, and the "electrical" zero is the one always used. It seems to make very little difference to the calibration of the instruments if there is quite a considerable difference between the "mechanical" and "electrical" zeros. It is important to have the centre of gravity of the needle in its axis as nearly as possible, otherwise it will tilt seriously when alive, and finally spark to the quadrants. I have done this by drilling two sets of two holes at right angles in the brass plate through which the axis passes, and holding the needle up successively by a loop of silk, the ends of which are passed through one set of holes, and then by another loop through the other set. By this means the needle is tested for balance about two axes at right angles to each other and to the axis of rotation. I had thought of putting the instrument in compressed air, but experience with a simpler arrangement was desirable, and up to about 7,000 volts on the needle, with 2 in. between the quadrants, it is quite satisfactory. This has limited the voltage used in the experiments, and for higher voltages either compressed air must be used or a dividing resistance or inductance for the needle, with consequent corrections of the uncertain errors which are indicated in the appendices. When testing good materials of low power factor under such conditions these errors promise to seriously vitiate the accuracy of the results. It may be of interest to note that the capacity current passing through the quadrants at earth potential and surrounding the earth-connected shield to the needle at 5,000 volts difference of potential, with a frequency of 50, was

Mr. Rayner.

34, 31·5 microamperes for the quadrants and 22 for the shield, totalling 87 microamperes passing through the needle suspension. The relative proportion between the two sets of quadrants depends, of course, on the deflection of the needle. The above readings were obtained when the needle was at zero and was unsymmetrical as regards the quadrants, and the two figures, 34 and 31·5, would become equal at the symmetrical position which was approximately half the full scale deflection.

With regard to Mr. Fleming's remarks, I have been able to stop a test on oiled cloth after visible damage occurred before actual puncture. The interval between the two is only a matter of seconds as a rule when no mica protection is used. A few preliminary experiments made with the wattmeter give some idea of the watts dissipated at breakdown, and by stopping just before this point it is possible to detect a slight local darkening of the material. I have as yet done no experiments in compressed air, and only one or two with uncertain results under oil.

With regard to Mr. Burnand's remark stating that the capacity of the dividing resistance ought to be compensated by inductance, it is, as I understand it, hardly correct. The wattmeter needle might be connected to any sort of potential divider, either pure resistance or pure capacity, or pure inductance, or any mixture of the three, provided the two portions of it are electrically similar, and that the capacity current of the needle did not disturb the system. The general increase in the power loss after renewing the experiments in Figs. 9 and 10 I put down to the buckling of the material when the compression is removed for examination. On starting again the material commences in a more buckled condition than when the previous run stopped, and the increased air-gap causes increased power loss. The reason that the experiments have been limited to about 15,000 volts is that this is about the limit of an electrostatic wattmeter at atmospheric pressure. I hope to continue the experiments at higher voltages.

Mr. Symonds asks whether more failures took place under long or short tests. This depends on the relative voltages used. The Pertinax tubes failed probably by reason of large decrease in ohmic resistance when warmed. The material becomes soft and was found to be deformed after the experiment—often with the mark of burning in the centre of the softened part.

Proceedings of the Five Hundred and Thirty-fourth Ordinary General Meeting of the Institution of Electrical Engineers, held on 22nd February, 1912—Mr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting, held on 8th February, 1912, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

Lawrence Birks.
James Caldwell.
Cyril C. T. Eastgate.
Arnold W. Mindo.

From the class of Associates to that of Members :—

Horatio H. Bentley.
John Ferguson.

From the class of Associates to that of Associate Members :—

Richard F. P. Blennerhassett.
Harold F. Buttenshaw.
Horace W. W. Henderson.
Frank A. Hill.
Norman Chas. Woodfin.

From the class of Students to that of Associate Members :—

Albert J. Anido.
Charles S. Atkinson.
James R. Beard.
Geo. S. Bradbury.
Kenneth D. Bullpitt.
Eric Thos. Caparn.
Evelyn Coad.
John J. Creasey.
Chas. E. Crossley.
Arnett R. Dunton.
Warren S. Dyer.
Bertram B. Grace.
Hugh Jack.
Percy C. Jones.
Emanuel Josephs.
Ronald S. R. Kneale.
Ardesher R. Setha.

From the class of Students to that of Associates :—

Wai Tsen Wang.

Messrs. A. E. Jackson and C. F. B. Marshall were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Member.

Samuel Alexander Pollock.

As Associate Members.

Frederick John Baldwin.
Sydney Harold Bill.
John Leslie Brown.
Bernard Frederick Browne.
William Burton.
John Henry Clarke.
Sidney John Eardley.
Frank Ellis.
Septimus Henry Fielden.
Harold Green.
Hermann Hotz.
Arthur Moorhouse Lawry.
Howard Schofield Longbottom.
Campbell Martin.
George Howard Nash.
Harry Anderton Nevill.
Mark Nicholson.
John Harry Pattman.
Arthur Preston.
Richard A. Tanham.

As Associates.

Clifford Stilwell Chaster.
Charles Joseph Henderson.
Lewis Oswald Monson.

As Students.

Edward Andreas Anderson.
Ernest Bernard Barlow.
Alexander Woodbine Bassett.
Herbert H. Bayliss.
Ewart Emlyn Birch.
Robert Hartley C. Brown.
Cuthbert Cartmell.
James Newlyn G. Chalk.
Armand Bruce Christen.
David Adam Christian.
Thedore Christian Christianson.
Cyril Burton Cripps.
Alfred George Cross.
Alfred Denton.
Frederick Charles W. Dixon.
William Dixon.
Cecil Duffitt.
Samuel Isaac Ellis.
Hughie Llewellyn Evans.
Earnest Arthur Fowles.
Leslie Dorey Francois.
Gilbert Frank Goodall.
Harold Gray.
Patrick Lancelot Hands.
Thomas Charles C. Hawthorn.
Henry Stanley Holbrook.
Percy Joe Humphry.
Alexander Bernhardt Johnstone.
David Jones.
John Reginald Kinsey.
Herbert Anthony Krasemann.
Hugh W. Lawrence.
Colla Ion Macdonnell.
Norrell Herbert Miller.
Leonard Ernest Mold.
Edward Llewellyn Morgan.
Percy Morrell.

ELECTIONS—*continued.*

Daniel Augustine Murphy.
Owen Thomas Owen.
Henry Dampier Phelps.
Richard Charles Philipp.
Charles Ponting.
Ernest Ralph Pullin.
Thomas Carr Richardson.
Joseph F. Roberts.
Richard Lewis Roberts.
Stanley Rhodes Rymer.
Charles Roy Saunders.
Laurence Sherowitz.
Isaac Smith.
Joseph Henry Thompson.
Joseph William Walker.
Stanley Ritson Walton.
Edward Marmaduke Webster.
Norman Wilkinson.
George Norman L. Woodley.

Donations to the *Library* were announced as having been received since the last meeting from A. R. Bennett, The Bombay Fire Assurance Association, B. Gati, H. S. Hallo, A. Heyland, The Institute of Chemistry, H. R. Kempe, F. Nöel-Paton, Physikalische Technische Reichsanstalt, Sir W. H. Preece, K.C.B., F.R.S., S. Rentell, E. and F. N. Spon, Ltd.; and to the *Museum* from A. Coleman, to whom the thanks of the meeting were duly accorded.

A paper by J. C. Macfarlane, Member, and H. Burge, Associate Member, entitled "The Supply and Transmission of Power in Self-contained Road Vehicles and Locomotives," was read and discussed see page 93).

THE SUPPLY AND TRANSMISSION OF POWER IN SELF-CONTAINED ROAD VEHICLES AND LOCOMOTIVES.

By J. C. MACFARLANE, Member, and H. BURGE, Associate Member.

Paper received 8th December, 1911, *and read before* THE INSTITUTION *22nd February,* 1912.)

INTRODUCTION.

Many electric drives and electric transmission gears have been proposed for road vehicles, but so far none of these have attained permanent success. Some time ago an attempt was made to introduce battery-driven vehicles of the heavy type for carrying passengers on the London streets, but it cannot be said that it was in any way successful, the causes being probably, lack of capital, unsuitable design of vehicle, and finally, the new police regulations with regard to weight. There cannot be any doubt that at the time when this attempt failed it was considered impossible to design an electric omnibus which would carry sufficient passengers to be remunerative, and be within the weight specified by the police authorities. That such a condition of affairs no longer exists will be evident from what follows in Section I. of this paper.

With regard to Section II., many types of petrol-electric vehicles have been designed, all of which are more or less variations of the following three systems, viz.: (*a*) an engine-driven dynamo supplying energy to a motor or motors connected to the driving wheels ; (*b*) the auto-Mixte system, in which the engine is connected directly to the road wheels through a dynamo-electric machine and clutch, the dynamo-electric machine acting alternately as generator or motor, charging the battery or helping the engine as required ; and (*c*) the Entz system and modifications, consisting of a dynamo, the field of which revolves, dragging after it the armature, the shaft of which is directly connected to the road-wheels, and has mounted on it the armature of a motor supplied with current from the dynamo. Series parallel control is usually adopted, the motor having two armature windings, and it is arranged at top speed to short circuit the dynamo, making it into a slipping clutch simply, the motor running idle.

The defects of the first system are evidently the large weight of electrical transmission gear and low efficiency. The chief defect of system (*b*) is that the engine must be large, due to the fact that the

speed of the engine must follow that of the vehicle, to avoid which is the main object of the petrol-electric drive. The defect of the third system is the complication involved in the series parallel control arrangements necessitating a double commutator motor and a complicated controller. Modifications of the latter system, however, promise to give good results in the future.

An ingenious system, due to Thomas, which might be classed under (*c*), allows of electromagnetic speed control from zero up to full speed. The electrical transmission gear, if properly designed, should give high transmission efficiencies and should be light. In order, however, to provide the means for reversing the vehicle, a battery or exciter is used. If a battery is adopted, self-starting of the engine and electric lighting can be provided, but if this battery were to fail it would not be possible to reverse the vehicle. Further, it is a pity that this battery is not made available for helping the engine during acceleration and hill-climbing, thus reducing the engine size and providing a means of recovering the energy stored in the vehicle, as a battery working under such conditions would keep in good order.

With regard to Section III., a proposal has been put forward which the authors consider is a suitable one for dealing with the suburban- and branch-line traffic of existing railway systems. The capital outlay necessary to electrify the termini of large railways in order to allow of better manipulation of the suburban traffic is so large that railway companies generally are very diffident in realising the enormous advantages to be obtained by adopting electric traction for this work. Any system, therefore, which permits of a considerable reduction in the capital outlay and shows a decided improvement on the annual charges is almost bound to have the immediate consideration of the large railway companies.

Apart from the financial side of the question, a decided advantage of the proposals outlined in Section III. is that in changing over traffic dislocations are reduced to a minimum, the change can be made as gradually as desired and on a small scale to commence with.

SECTION I.—ELECTRIC VEHICLES.

1. Limitations of Heavy Petrol-driven Vehicles.

At the present time the popular means of driving heavy commercial vehicles in this country is by the petrol engine, and this is fairly satisfactory where long non-stop runs have to be made through level country. In large cities, however, the problem is entirely different, and, constant starting and stopping being a necessity, it is surprising that practically no successful attempt has been made to meet these conditions. The inflexibility of the petrol engine makes it at once a difficult matter to design heavy vehicles to withstand the continual starting and stopping that is necessary in city traffic, where in nearly every case (depending on the number of stops) the energy consumed

during acceleration is considerably more than that required to get from point to point at constant speed. This necessitates a large engine, generally three to four times the size that would be required to drive the vehicle on the level, which, when running at high speed and developing low power, must be very inefficient. The above condition is aggravated by the fact that a lowering of the speed on the engine (which must take place until the gear is changed) involves a loss of compression, inefficient action of the carburetter, affecting adversely the power developed.

Other disadvantages of the petrol engine for this service arise out of the multiplicity of parts, such as the silencer, water pump, radiator, oil tank, oil pipes, petrol tank, petrol pipes, sparking plugs, inlet and exhaust valves, etc., all liable to get out of order, due to shock, vibration, and the continual variation in engine speed; and omnibus companies require a large night staff for continual observation and adjustment.

It is well known that as regards the petrol omnibus in London, especially if badly driven, the transmission gear is the most expensive item in the upkeep; and even the body, chassis, wheel, and tyre upkeep must be high, due to the fact that the braking is often very uneven; also the changing of the gears introduces inertia strains.

In addition to the inherent disadvantages of this type of vehicle, if it is remembered that the gear is entirely at the mercy of negligent or malicious drivers, it is evident that there should be a demand for a vehicle from which these difficulties have been eliminated.

2. The Inherent Advantages of Battery Traction for City Work.

The authors have no doubt that the remedy lies in adopting secondary batteries as a source of power for heavy vehicles of all kinds for city traffic, more especially if complete regenerative control is adopted and the batteries are maintained by the makers.*

The reasons for this are fully dealt with in the paper, but are briefly as follows, and are applicable to any electrically driven vehicle :—

1. The absence of shock and vibration greatly reducing the wear and tear.
2. The reduction of rates following on the supply of current for battery charging from municipal stations.
3. From the owner's point of view there are many advantages, some of which are: Lower cost of insurance and freedom from insurance limitations; instant readiness of vehicle and less depreciation, resulting in less time in the repair shop, so that a larger percentage of vehicles are kept running. This involves a reduction in capital, rates, rent and taxes, insurance, supervision and establishment charges. In the

* The routine, of course, in regard to batteries would be the usual one, *i.e.*, for one-half the batteries to be under operation in the streets, and the other half under charge and inspection at the garage.

case of omnibuses, due to better lighting and other public advantages, the takings are bound to be considerably augmented, and further additions to revenue might be obtained from novel forms of advertisement and electric signs on the vehicles.

In the near future also it is almost certain that legislation will favour electric traction for city work.

Incidentally there is no circulating water to freeze, and no oil is required, the lubrication of the battery vehicle being carried out by grease. Further, it is not necessary for the driver to leave his seat for the purpose of starting up, and therefore the vehicle while stationary is not absorbing power.

The charging of batteries from municipal supplies has already been mentioned, and authorities concerned should be highly interested in this matter when it is pointed out that practically no capital expenditure is required or additions to the working expenses, and that the energy can be delivered off the "peak." It will be seen that even if the supply is cheap, the income to be derived by stations will be nearly all profit.

Taking energy at ½d. per unit, 1,500 electric buses running in a city, each consuming 1 unit per mile, and making 30,000 bus-miles per year, would provide an income for the power station of £100,000 per annum, apart from the additions to the lighting load that would naturally accrue. Surely this is well worth fighting for, seeing that it is obtained with practically no outlay.

3. Some Reasons why Electric Road Traction has not Made Headway.

The conditions being so favourable to electric buses, there must be reasons why these have not made headway.

One of these is unquestionably that of weight as laid down in the police regulations. Hitherto traction batteries for a 6-ton vehicle have weighed about 2 tons (consuming energy at well over 1 unit per mile, *i.e.*, 2 units per mile for charging purposes), and it was therefore impossible to construct omnibuses carrying a sufficient number of passengers to be remunerative. A more important reason, however, was the unsatisfactory working of the battery itself, which now appears to be preventible with proper care as exemplified by the fact that there are some 10,000 electric vehicles of all kinds constructed annually in America. It has been recognised, however, that the battery is the weakest link in the chain of the electrically driven vehicle, and one of the objects of this paper is to describe a system which to a great extent removes the weaknesses of the battery and considerably strengthens the position of the battery vehicle from other points of view.

4. Description of a System which Eliminates Battery Difficulties.

Apart from minor alterations in the battery itself, most of the improvement has been obtained by raising the vehicle efficiency with a

consequent reduction in the size of the battery for a given mileage. Resulting from this, the initial and upkeep costs are reduced in almost direct proportion to the reduction in the size of the battery, but more important still, the ratio of the live to the dead load has been increased almost as the square of the reduction in battery weight.

Some of the methods that the authors have adopted to bring about this result comprise :—

(*a*) Braking entirely by regeneration, the battery absorbing the energy returned.

(*b*) A controller in the shape of a very efficient rotary transformer or automatic electric valve (only transforming half the power supplied to the wheel motors) which automatically limits the current that can be drawn from or returned to the battery, displacing the usual series-parallel type of controller.

(*c*) A motor with special shunt field windings, having a torque speed characteristic similar to a series motor.

It has already been mentioned that the battery current is limited to a predetermined value under any conditions of speed, *i.e.*, the automatic valve only allows a safe amount of power to pass from the battery to the driving motor under the worst conditions of driving, and thus the capacity of the battery is retained.

Altogether it will be seen that the battery is used under very favourable conditions indeed, and it should also be noted that the regenerative action of the motor comes into play whenever the driver reduces the speed or stops the vehicle.

As traffic conditions compel a large number of starts and stops, the battery becomes more of the nature of a "buffer" battery, the life of which, as is well known, is greater than that of a battery being discharged during the whole time the vehicle is in commission. This has been demonstrated by applying a low-frequency alternating current to the terminals of a battery cell, discharging and charging the cell during 1 cycle, when it was found that the ampere-hour and watt-hour efficiency were extremely high, and the life very much greater than that under ordinary conditions.

The scheme as applied to the driving of heavy electric vehicles is shown in Fig. 1. The automatic electric valve A B, used as a controller, possesses the further property of acting as a power-limiting device between the battery and the motor. The action of this machine under full-speed conditions is as follows:—

The upper half (A) of the armature acts as a motor, and is coupled directly across the battery. The lower half of the machine marked (B) acts as a generator and is coupled in series with the driving motor (C), so that the latter is receiving across its terminals twice the battery voltage. The motor (C) is provided with two shunt field windings, one of which (D) is connected across the battery, providing a constant excitation, and the other (E) across the terminals of (B).

The winding (E) is arranged so as to assist the winding (D) during the acceleration period, and to oppose (D) when running at full speed. The part (B) of the electric valve is provided with a variable and reversible excitation by the winding (F) and controlled by the regulator (G). When the regulator arm is over to the right, say, (B) adds its voltage to that of the battery, but when the regulator arm is to the left this voltage is subtracted from that of the battery. With the regulator arm in the mid-position (B) is not excited. An additional winding (H) is also provided on the field of (B) in series with

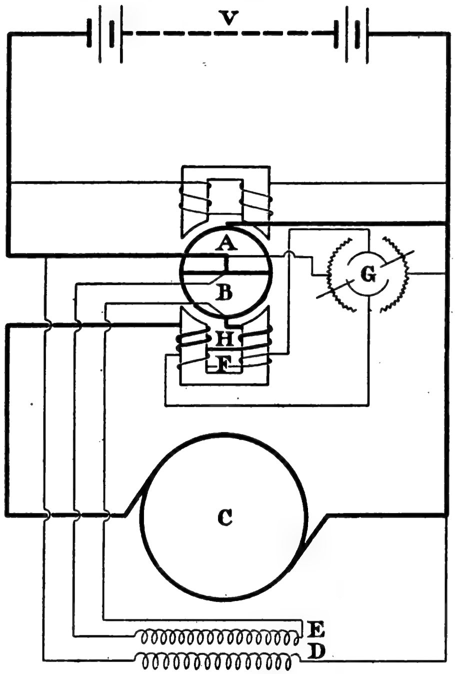

FIG. I.—Diagram of Connections. (Battery Vehicle.)

the driving motor (C) which opposes the winding (F) when (B) is acting as a generator delivering power to (C).

The advantages of this arrangement are as follows: During the period of negative acceleration, when the motor is returning energy, the field of the motor is strengthened so that the electrical braking tendency is largely increased, whereas when the motor is being accelerated and is rotating rapidly its field strength is diminished so that acceleration is facilitated. The design of the motor is such that due to the action of the field winding (E) the torque produced is nearly proportional to the square of the current passing through the motor armature. Thus, when starting or hill-climbing, with the controller

"full on," the torque is four times that on the level, with only two and a half times the normal current in the armature.* Moreover, by means of the series winding on (B) the current to the motor (C) is always kept within safe limits when it is driving as well as when it is braking. To take a concrete example : Assume the battery gives 60 volts, and that the part (B) of the electric valve also gives 60 volts. If (B) be fully positively excited with the regulator arm to the right, its voltage will be added to that of the battery and there will be 120 volts across the driving motor terminals; thus it will be capable of rotating at full speed, and the voltage across the winding (E) will be the full negative value, so that the field strength of the driving motor is that due to (D—E). If, however, owing to an increase of the load of the driving motor its speed should fall, the increase current flowing through the winding (H) will reduce the field of (B), and thus lower the voltage on the driving motor, whereby any danger of burning out is avoided. When the speed of the motor drops the winding (E) has its full E.M.F. reduced (due to the voltage across the terminals of (B) falling), thus in every case strengthening the motor field progressively as its speed falls. When the regulator arm is fully to the left (B) is developing a counter E.M.F. of 60 volts (or more), and there will be no E.M.F. across the driving motor, which will therefore come to rest. When the back E.M.F. of the motor rises above the voltage supplied to it, so that the motor is returning energy to the battery, the field (H) tends to increase the voltage of supply in order to limit the amount of current returning to the battery.

The entire control is carried out by means of a foot-pedal and a single reversing lever which is also employed to start up the machine (A B). The pedal controls the reversing field regulator (G), and when in the "off" position the arm is over to the extreme left, and if allowed to come quickly to this position a very powerful braking effect is produced, which continues even after the vehicle has been brought to rest. The latter effect is obtained by arranging the resistance of the regulator (G) so that (B) gives a back E.M.F. slightly in excess of the voltage of the battery, producing a negative current of no power through the armature of the driving motor, and giving a torque in the backward direction. This torque is arranged to be of such a magnitude that it holds the vehicle on a comparatively steep downward gradient, and yet has not sufficient power to cause the vehicle to start backwards on the level. If, however, the vehicle is facing uphill with the controller in the "off" position it is necessary, in order to prevent the vehicle from moving backwards, to depress the controller pedal slightly and give the driving motor a positive torque, tending to drive the vehicle uphill. This torque can be arranged to keep the vehicle stationary on the hill, thereby dispensing with the use of any mechanical brakes.

* The C^2R losses throughout are therefore kept low, resulting in a high efficiency even at low speeds. Besides reducing the losses, this arrangement is valuable because the electric valve can be made smaller.

It will be readily seen that a vehicle equipped with such a system has the advantage that the speed is adjusted automatically to the gradient of the road. In fact, the speed is a definite function of the torque required to drive the vehicle. The above statement applies to all positions of the controller pedal, as indicated in Fig. 2, where the dotted curves show the output to the motor for intermediate positions. Fig. 3 shows the electrical characteristics of the system for maximum power position of the controller as a function of the vehicle speed.

5. Summary of the Salient Features of the System.

Battery.—Due to economical acceleration, regeneration, high torque per ampere, and other causes, it is possible to obtain a higher efficiency, and therefore reduced battery weight and size (*i.e.*, about half the energy consumption and weight for the same number of passengers and mileage as on previous battery omnibuses).

Further, as the voltage of the battery is only half that of the motor, the number of cells can be reduced without additions to the weight of other parts. This admits of a further reduction in the weight, due to fewer cases, connections, less liquid, etc. Also, as the discharge rate of the battery is limited, the capacity is greater under working conditions, *i.e.*, the ampere-hour efficiency is high. Further, it is obviously not necessary to use two motors or a double commutator driving motor to obtain economical speed control; therefore a further increase in order in the efficiency of the system is obtained.

Thus the energy, initial and upkeep costs are reduced, and the ratio of live to dead load is very much increased.

Control.—The control is very simple, the whole operation being effected with one foot-pedal. It is fool-proof, and any prearranged maximum battery currents are obtained for definite vehicle speeds. These values cannot be exceeded by any means within the power of the driver. Pressing down the pedal increases the speed; raising the pedal reduces the speed, and at the same time applies regenerative braking.

The acceleration or retardation is proportional to the rate of forcing down or raising the pedal, and these have been arranged as a maximum to get up speed from standstill in about one and a half to two bus-lengths, and to brake to a standstill from full speed in the same distance. Any intermediate positions of the pedal give intermediate speeds, and continuous crawling can be done at the rate of one-hundredth of a mile per hour if required.

One brake can be dispensed with if police regulations permit, and it is not even necessary to use any mechanical brake when driving in the ordinary course.

The system of braking reduces the tendency to skid on greasy roads, and as the controller always returns to the braking position, this action brings the vehicle to a standstill if anything happens to the driver.

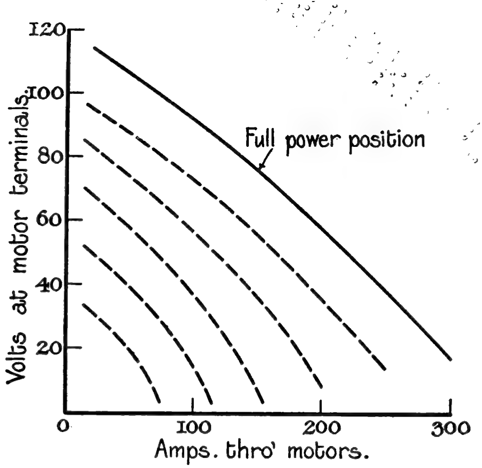

FIG. 2.—Output Characteristic of Rotary Transformer for various Positions of Controller Pedal.

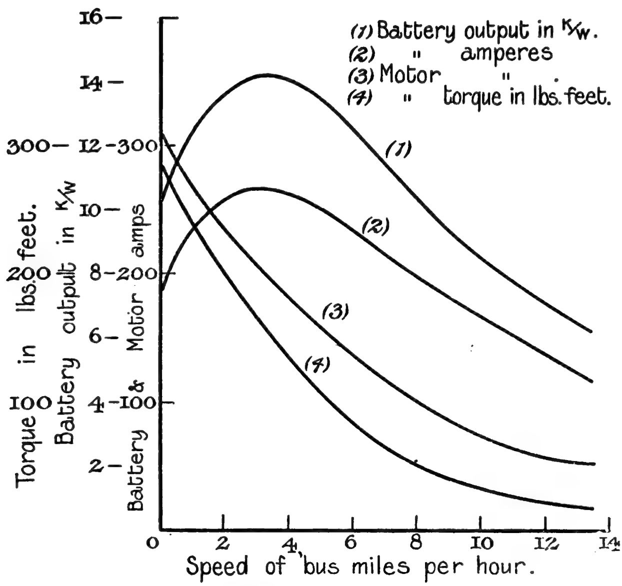

FIG. 3.—Battery Vehicle Characteristics.—Controller Pedal "Full On."

6. Some Details of Weight and Design of a Battery Omnibus.

An omnibus constructed at Chelmsford and equipped with the system outlined above is now running in London, and conforms in all points with the Metropolitan Police Regulations, and when loaded it has a total weight of not more than 6 tons. It is fitted with a battery having a capacity of 500 ampere-hours on a 5-hour discharge rate. The battery is mounted in front in the position usually occupied by the petrol engine, therefore no swinging bolts or clamps are required for its support. Ordinary apparatus in the way of cranes or blocks is all that is necessary to remove the battery and replace it by another.

	Cwts.	Qrs.
Battery, comprising 28 cells, 500-ampere-hour capacity, including acid, terminal connectors, at 75 lbs. per cell	19	0
Battery case complete, including lifting hooks and eyes, cover and bonnet	2	0
Electrical equipment complete, including electric valve, motor, regulator, starter, and wiring ...	7	0
Body, including destination boards, driver's seat, lighting circuits, fire extinguisher	19	3
Tyres	4	3
Wheels	5	1
Back axle, including cardan shaft, differential reduction gearing and ball-bearings complete ...	4	2
Front axle, including all ball-bearings	1	1
Steering gear complete	1	1
Chassis complete, including springs and all attachments for springs	7	1
Two sets of mechanical brakes, including brake drums, levers, rods, etc.	1	2
Total dead weight	73	2
Total live weight, 34 passengers, driver and conductor, at 10 stone each	45	0
Grand total	118	2

Further, in this position it is much freer from dust and dirt—a point affecting its life—and it is more easily inspected and repaired. In the previous omnibuses running in London the battery was suspended from under the frame and liable to get very dirty, and if any of the connectors on the cells under the chassis gave out in the middle of a journey it was almost impossible to carry out repairs on the spot.

Fig. 4 shows the outline of the chassis of the latest design of omnibus, to which is fixed the automatic electric valve and motor,

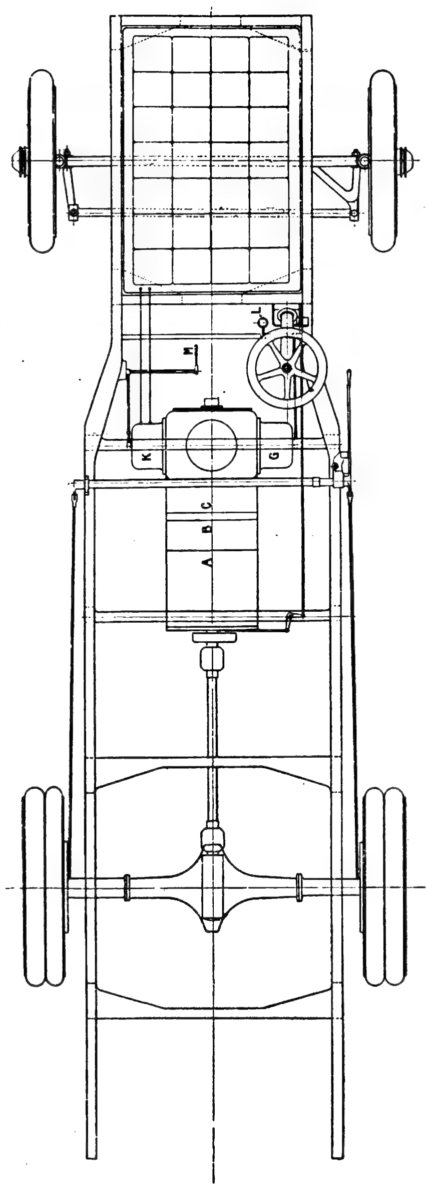

FIG. 4.—Plan of Chassis. (Battery Vehicle.)

all in one case and marked (A), (B), (C). The case is hung to the chassis frame by means of suspension hooks and eyes and is stayed to the sides of the chassis by rods. The motor drives direct through the cardan shaft to the worm-reduction gearing mounted on the usual construction of live axle. The regulator (G) is fixed on one side of the electric valve, while the starter (K) is mounted on the other side. The foot-pedal (L) and the starting and reversing lever (M) are linked up to the regulator and starter respectively by means of rods, as shown.

The weights are detailed on page 102.

The dimensions of the battery over cells when packed closely are 49 in. × 31 in. × 16¼ in., making it of a convenient size for placing in front of the omnibus in the position usually occupied by the petrol engine.

From the figures given above for the total weight of the equipment, excluding the battery, it will be seen that this is extremely small and compares very favourably indeed with an equipment of the series-parallel control type for the same speed and loaded weight.

7. Energy Consumption.

With battery vehicles the question of energy consumption is of the utmost importance, for by reducing this the battery weight for a given mileage can be less.

Fig. 5 shows a chart of ¼-minute readings of the battery discharge taken on a loaded omnibus (6-ton weight) on a run from Chelmsford

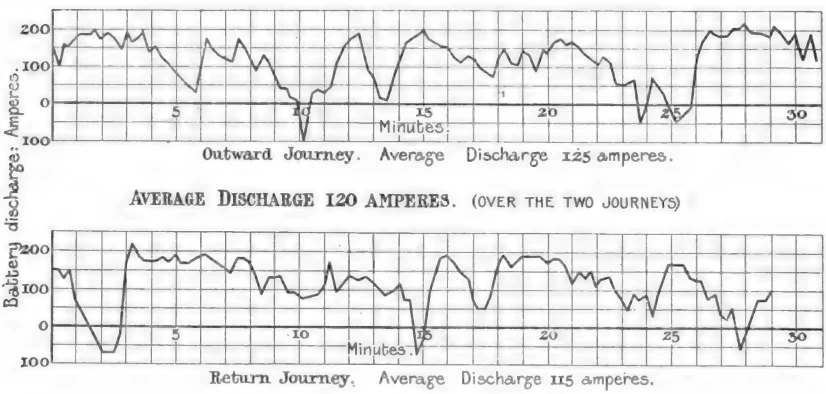

FIG. 5.—Chart of Discharging Currents. (Battery Vehicle.)

a distance of 6 miles out and 6 miles home. There were one or two fairly steep hills to be negotiated, and an examination of the chart will show these, especially the down grades. The readings were taken with the controller pedal on the "full on" position the whole of the time, the omnibus speed only varying due to the contour of the road. The average speed was just under 13 miles per hour, the average current consumption on the outward journey was 125 amperes and on the back

journey 115 amperes, making a total average of 120 amperes. The ampere-hours per mile therefore work out at just under 10, and as there are 28 cells giving a discharge of 120 amperes at about 53 volts the energy consumption per mile was equal to 0·53 of a unit, or, in other words, 88 watt-hours per ton-mile, and the average horse-power required to drive the vehicle at a speed of 12¾ miles per hour was just under 8½ H.P.

It will therefore be seen that as the battery has an average capacity of 500 ampere-hours the total range of the vehicle is 50 miles.

8. Comparative Cost per Bus-mile of Running Electric and Petrol Omnibuses in London.

The following items in the cost of running are common to both types, although not necessarily equal in each type—*i.e.*, tyre maintenance, drivers, conductors, body upkeep, traffic expenses, washing, rent, rates, water, gas and lighting, depreciation, taxes, supervision and establishment charges.

Other items that are widely different in cost are as follows :—

	Electric Vehicle (Pence per Bus-mile).	Petrol Vehicle (Pence per Bus-mile).
Battery maintenance	2·00	—
Power or petrol	0·50	1·25
Chassis maintenance	0·10	1·00
Lubricating oil and paraffin	0·01	0·22
Vehicle lighting	—	0·10
Insurance (not including third party risk)	0·10	0·20
Washing and preparing for running ...	0·17	0·90
	2·88	3·67
Depreciation (explained below) ...	0·72	1·03
Comparative cost	3·60	4·70

As regards the above comparative cost the important figures are quite definite, those for the petrol vehicle being obtained from the best actual practice. On the other side the battery maintenance and power figures are already fixed by the battery manufacturers and the electric supply companies respectively. In comparing the chassis maintenance in the two cases the maintenance of the engines, gear-box, clutches, and mechanical brakes are to be set against a low-voltage electrical equipment consisting of two machines, a starter, and a shunt regulator.

On a basis of 30,000 bus-miles per annum, a sum of £13 per bus per annum is allowed for the electrical equipment, gearing, etc., a figure very much on the high side when it is remembered that there is no wear on mechanical brakes and the retardation is uniform.

The above table shows roughly that the electric omnibus is the

cheaper to run, and when items of cost which are common to both types are reviewed, the case for the electrical vehicle is still better. Taking these in detail, the cost of tyre maintenance, drivers, and body upkeep is undoubtedly less, and the following argument will show that rents, rates, supervision, establishment charges, and depreciation are less. Out of a fleet of petrol vehicles a large percentage (as seen by the maintenance figure), roughly 25 per cent., will be out of commission, and more space in the garage and larger repair shops are required as compared with the electrical omnibus. This also means a greater capital expenditure per bus-mile.

As regards depreciation, the two cases have to be compared on the same capital basis, for although the electric vehicle will be rather more expensive when the battery cost is included, the battery makers maintain this at its full value, and thus depreciation of the electric vehicle is undoubtedly less than the petrol vehicle. Suitable figures for these are 10 per cent. and 15 per cent. per annum respectively, making the figure for the depreciation of the electric bus 0·72 and the petrol bus 1·03 per bus-mile.

It would appear therefore that the electrical omnibus can be run for at least 1d. per bus-mile less than the petrol, and before concluding this section of the paper the fact should be emphasised that the revenue per bus-mile should be greater due to the following advantages :—

1. No noise, no smell, no filth.
2. Starting up with uniform acceleration and without shock.
3. No vibration due to reciprocating parts.
4. No jar due to clutching while running up, change of speed, or braking when stopping.
5. The brilliant and clean lighting of the interior and exterior of the vehicle.
6. The public safety, due to the fact that the bus is so easily controlled and the maximum speed is limited. Due to electric braking, the tendency to skid is more easily controlled than in other forms of buses, as the pedal always returns to the "off" position when freed. If any accident occurs to the driver the vehicle will come to a standstill.
7. Facilities for novel forms of advertising.

9. Other Advantages Summarised.

1. The vehicle can be immediately started or stopped.
2. The control is fool-proof, through having only one pedal to operate whilst driving.
3. The braking is also carried out by means of the pedal, and only on very rare occasions will it be necessary to use the mechanical brakes. Even when standing on a hill these will not be necessary.
4. No adjustment *en route.*
5. Will develop full power under any conditions of weather.

In conclusion, the arguments in this section apply equally in many points to heavy commercial vehicles, especially where these are operating in city traffic on round journeys.

SECTION II.—PETROL ELECTRIC VEHICLES.

1. Limitations of the Electrical Vehicle.

As already indicated in Section I., there are two conditions necessary and essential to successful battery traction for heavy road vehicles. In the first place, the charging stations must be within a definite range, and secondly, the battery should always be kept under the supervision of the makers, otherwise the cost of its maintenance would be prohibitive. It is obvious, therefore, that the electrical vehicle is unsuitable for travelling long distances or working in outlying districts. Engine-driven vehicles with mechanical transmission gear have hitherto held this field, but all the undesirable features emphasised in Section I. still exist, although possibly to a less extent. The petrol drive would be an ideal one if it were possible to start the engine up and run the vehicle at full speed for the whole journey on the level, but this is of course impossible, owing to the fact that there are hills to be encountered and turns and traffic on the road to be negotiated.

2. Electric Transmission Gears.

To overcome the inflexibility of the mechanical transmission gear, an electric transmission (with and without a battery) between the engine shaft and the road-wheels has sometimes been introduced with success. There is no reason why a properly designed electric transmission gear should not be superior in every way and have advantageous features unobtainable with the mechanical gear. For instance, if the arrangement includes a small battery, we have at once the advantages of electric lighting, self-starter for the engine, reserve of power for hill climbing, and the possibility of electric braking. It may be said that it is a pity to introduce a battery at all on such a vehicle, but when the many advantages are considered it will be agreed that the battery is a very useful part of the equipment. The life of such a battery will be very good, due to the fact that it is only supplying power for starting and climbing hills, and although it has to give fairly large discharges at times, the average current is very small; that is to say, the average discharge rate is low in comparison with its capacity in ampere-hours, and therefore its life is correspondingly greater reckoned in vehicle-miles.

3. Description of System.

It is suggested that the all-electric system modified by reducing the battery to one-fifth the capacity, and by adding a 9-H.P. air-cooled engine would meet the case. Fig. 6 shows the arrangement, and the method of operation is very similar to that of the all-electric system.

The engine X is coupled to the electric valve A B and takes the average load, the peaks being supplied by the battery V which also absorbs the energy returned during braking. When the output of the battery is equal to that of the engine (a condition which holds during middle portion of the acceleration period, and when climbing hills) A carries no current, resulting in a very high overall efficiency, about 86 per cent., through the electric transmission gear. In order to make the battery respond to the varying loads without appreciable variation of the engine speed, the part A has a field winding which

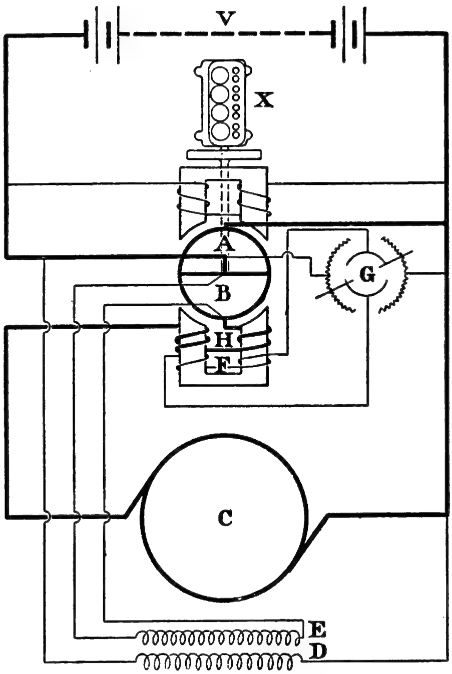

FIG. 6.—Diagram of Connections. (Petrol-electric Vehicle.)

gives it a falling E.M.F. when the motor demands large power and a rising E.M.F. when the motor is regenerating.

4. Summary of the Salient Features of the System.

Battery.—This is an ordinary buffer battery constantly charging or discharging automatically within safe limits, according to the nature of the road, and as such works under very favourable conditions approaching the case of the battery supplied with alternating current mentioned in Section I. Besides acting as an equaliser, other important functions of the battery are :—

(*a*) To start up the engine from the driver's seat, a very great convenience, and to supply current to the sparking coils.
(*b*) To enable the vehicle to run to a garage in the event of an engine breakdown.
(*c*) To light the vehicle and to provide current for electric signs and advertisements.
(*d*) To allow of electric braking down to any speed.

Engine.—The engine runs practically at constant speed, and has only to supply the average power required to drive the vehicle. It is well known that to drive a 6-ton loaded vehicle on the level at 12 miles per hour, 9 B.H.P. is required. Now, when running at about half-speed uphill, in this system the gear ratio automatically changes, enabling the full 9 H.P. to be utilised; the torque therefore under this condition is twice that developed on the level. Further, with the aid of the battery, the motors are enabled to develop an additional 9 H.P., making a total of 18 H.P. at this speed, thus giving four times the normal running torque. A petrol vehicle, however, running up the same hill at half-speed on the top gear would have to be equipped with a 36-H.P. engine on the normal full-speed basis, because at half-speed it would only just be able to develop the 18 H.P. required. It may be argued that an earlier change of gear would enable a smaller engine to be used, but even this will not necessarily compensate for the falling off of power due to loss of compression and inefficient action of the carburetter, and it is a fact that 36- to 40-H.P. engines are actually fitted to such vehicles.

In the proposed petrol-electric system the engine power necessarily is not large, and its speed being constant, air-cooling for the engine is possible with its attendant advantages—*i.e.*, simplicity, reduction in space and weight, and the absence of freezing troubles. A governor is used to keep the engine speed constant, thereby removing all sources of shock and inertia stress, due to the manipulation of the spark or sudden variation of the engine speed when clutching or changing gear and allowing an engine design with high initial compression. The load factor being approximately 100 per cent., the consumption of petrol will not be more than half that of the ordinary petrol vehicle, the engine of which works on the average at only one-third full power.

Control.—The operation is as follows: The starting switch is put over either in the forward or reverse position, as required, and the engine is thus started up and begins to fire, charging the battery at normal current. The pedal is then depressed and the motor is fed by the combined power of the engine and battery, the opposing series coil on A allowing the battery to give its share. On reaching full speed the power absorbed by the motor falls to the average—*i.e.*, 9 B.H.P. —which is given by the engine while the battery floats. On raising the pedal the motor returns energy to the battery, and in so doing tends to raise the speed of the machine A B, and the governor meanwhile cuts

off the power from the engine. When the regeneration has ceased the engine continues to charge the battery. Other features of the control are already outlined on page 100, Section I., all of which apply equally in both cases, but it may be mentioned here that due to economical acceleration, high torque per ampere and regeneration, the efficiency of the system is very high, and also one mechanical brake can be dispensed with.

5. Comparative Weights and Simplicity of System.

In order to obtain a comparison between the petrol-electric and the petrol vehicle, the case of the 34-passenger omnibus will again be considered, as it is the only type of heavy vehicle for which very definite figures are available. It is well known that the weight of the modern petrol vehicle complete with lubricating oil, petrol, and water, is 5 tons 18 cwt., and the following table shows the detailed weights of the petrol-electric vehicle constructed on the above system :—

Table showing Detailed Weights of Proposed Petrol-electric Vehicle.

	Cwts.	Qrs.
Engine, including silencer and full petrol and oil tanks	1	3
Battery,* capable of giving a discharge of 50 ampere-hours on the 1-hour rate, and including the containing case and all connections	6	1
Complete electrical equipment, as described under Section I.	7	0
Body, including destination boards, driver's seat, lighting circuits, fire extinguisher, etc. ...	19	3
Tyres	4	3
Wheels	5	1
Back axle, including cardan shaft, differential reduction gearing, and ball-bearings complete	4	2
Front axle, including all ball-bearings	1	1
Steering gear complete	1	1
Chassis complete, including springs and all attachments for springs	7	1
Two sets of mechanical brakes, including brake drums, levers, rods, etc.	1	2
Total dead weight	60	2
Total live weight, 34 passengers, driver, and conductor at 10 stone each	45	0
Grand total	105	2

* The dimensions of the battery are 24 in. × 24 in. × 12½ in. high, making it a convenient size for placing under the driver's seat.

This weight is under that of the petrol omnibus mentioned above.

The simplicity of the two systems can best be compared by tabulating in the following manner the various parts which affect the question :—

TABLE SHOWING COMPARATIVE NUMBER OF PARTS OF PETROL-ELECTRIC AND PETROL VEHICLES.

	Petrol-electric Vehicle.	Petrol Vehicle.
Source of power ...	Light engine and battery ...	Heavy engine.
Engine cooling ...	Air	Water, radiator, pump, and pipes.
Transmission gear	Electrical equipment	Gear box and clutch.
Engine starter ...	—	Starting handle or motor, and cells.
Lighting	Electric	Oil lamps, gas cylinder or dynamo, and battery.
Brakes	One set	Two sets.
Size of petrol tank	50 per cent. ...	100 per cent.
Total weight of vehicle	5 tons, 5 cwts., 2 qrs.... ...	5 tons, 18 cwts.

6. ENERGY CONSUMPTION AND COST OF RUNNING.

The consumption of energy is not in this case of such utmost importance as in the case of the all-electric vehicle, but it is of some importance from the point of view of petrol cost per mile and the size of the buffer battery. Fig. 7 shows a chart of the charge and discharge of a buffer battery, and was obtained by fitting a petrol engine to the chassis of the electric bus described in Section I., and running the vehicle over a road of average contour. It will be seen later that the engine has supplied the average load of the omnibus throughout a 12-mile journey out and back, and that the hills have been dealt with by the battery. Looking further into this diagram, the dotted straight line gives the average value of the complete discharge that the battery obtained during the 6-mile inward run, and it will be noticed that this was about 17½ amperes, although the maximum went up in some cases to 110 amperes. As the discharge was 17½ amperes at 53 volts, taking the watt inefficiency of the battery at 25 per cent., the average power to drive the vehicle (*i.e.*, 8½ B.H.P., see Section I., page 105) has to be raised by about 0·35 H.P. to deal with this. If, therefore, the engine is designed to give 9 H.P. this should be large enough to give a mean speed of 12 miles per hour. The petrol consumption of such an engine would be about 0·75 pint per B.H.P. per hour, and therefore the vehicle would travel approximately 14 miles with a gallon of petrol,

making a cost of 0·75d. per mile for power, taking petrol at 10½d. per gallon.

With regard to the battery, a suitable capacity would be 50-ampere hours at a 1-hour rate (*i.e.*, one-fifth of the capacity of the all-electric battery) capable of giving discharges of 225 amperes for 5 minutes, and providing for that time an additional 16 H.P., making the total power available 25 H.P. at any speed, if required. This battery is only discharging at the average rate of 17½ amperes, which is one-third of its normal, and therefore the life in vehicle-miles is three times that of the all-electric vehicle battery, the maintenance figure for which was 2d. per mile. Compared on the same basis, the maintenance figure for

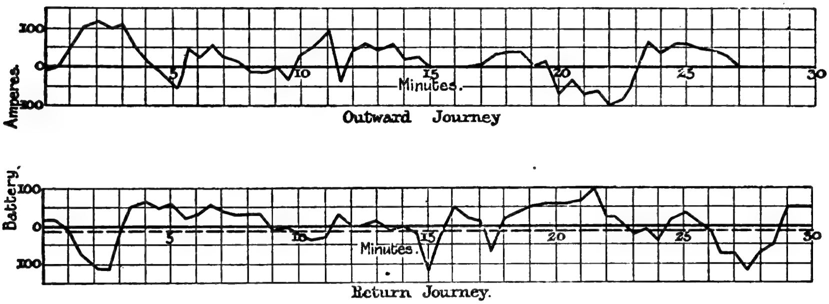

FIG. 7.—Chart of Battery Charging and Discharging Currents. (Petrol-electric Vehicle.)

this battery should be one-fifteenth part of 2d., *i.e.*, 0·134d., but owing to the fact that the discharge rates are sometimes high the figures will be increased to 0·35d. per vehicle-mile.

7. Comparative Cost of Running Petrol-electric and Petrol Omnibuses.

The table on page 113 gives the comparative cost of those items which are widely different in the two systems.

All the remarks made in Section I. with regard to the items of cost which are common to both types, viz., tyre maintenance, conductors, drivers, body upkeep, rents, rates, water, gas, lighting, supervision, and establishment charges apply almost equally to the petrol-electric vehicle. With regard to the question of depreciation, it has been assumed that the depreciation of a petrol vehicle is 15 per cent. against 12 per cent. of the petrol-electric vehicle, and the figure tabulated above has been reckoned on that basis.

In conclusion, it would appear that the petrol-electric vehicle, constructed on the above lines, would cost less to run than the present vehicle by at least 1¼d. per mile.

	Petrol-electric Vehicle (Pence per Bus-mile).	Petrol Vehicle (Pence per Bus-mile).
Battery maintenance	0·35	—
Petrol	0·80	1·25
Chassis maintenance, including engine and transmission gear ...	0·50	1·00
Lubricating oil and paraffin	0·10	0·22
Vehicle lighting	—	0·10
Washing and preparing for running...	0·50	0·90
	2·25	3·47
Depreciation, explained below ...	0·9	1·03
Comparative Cost	3·15	4·5

Most of the advantages listed at the end of Section I. apply equally to the petrol-electric vehicle.

SECTION III.—OIL-ENGINE ELECTRIC SYSTEM FOR SUBURBAN RAILWAYS.

Considerations affecting the Question.

Many railway companies have been looking into the question of electrifying their suburban lines, to meet more successfully the competition of tramcars and omnibuses. Where electrification has been carried out the superior acceleration and comfort together with the large seating capacity attained has invariably won back the traffic lost for the time being.

On the other hand, however, the companies have been unable or disinclined to face the enormous outlay involved in the installation of generating station, sub-stations, third rails, etc., and for existing lines, apart from the cost of converting, the complication of conducting rails or overhead wires at large junctions and termini is generally objectionable.

Proposals Outlined.

It is suggested therefore that a self-contained electric train with complete regenerative braking would meet the case, and it will be shown as far as possible that the capital outlay apart from the cost of a generating station would only amount to approximately two-thirds of that required where the power has to be transmitted from generating stations and fed to the train by conducting rails.

The trains would be made up of any number of motor coaches and

trailers on the multiple unit system, a diagram of connections for such being illustrated in Fig. 8, from which it will be seen that it is possible to drive from any motor coach in the usual manner, and that only three relay train wires are necessary.

The motor coach is equipped with a spirit or oil engine and electrical equipment similar to that described under Section II., but to provide in suburban trains the very large additional power required during acceleration, and to absorb the returnable energy, a larger proportion of battery is carried on the train. The question may be raised that the battery will make the equipment very heavy, but it will be seen later that this is not necessarily the case. Allowing this to be so, however, the possibility of recovering at least 75 per cent. of the energy stored in the train minimises the objection to additional weight.

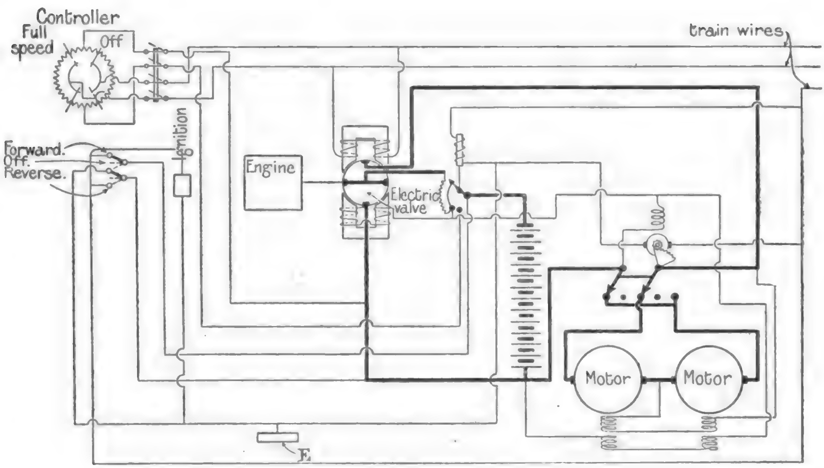

FIG. 8.—Diagram of Connections. (Oil-electric Motor Coach.)

As shown in Section II., only a comparatively small engine is required, developing power sufficient to overcome all train friction, battery, and other losses, and running at constant speed and power throughout the whole journey.

The other advantages of a battery already mentioned in Section II. apply equally in this case, but the advantages of a battery are especially evident when it is remembered that roughly four times the average power is required during the acceleration period, and that 75 per cent. of this is available for charging the battery during retardation; also all wear on brakes is eliminated.

BATTERY AND ENGINE SIZE CONSIDERED.

In order to determine the size of the battery, the acceleration and retardation rates will be assumed constant and of equal period, also the

speed after acceleration is finished will be assumed constant until retardation begins. The diagram Fig. 9 shows clearly the assumptions. It may be mentioned here that it does not matter whether the rate of acceleration is constant or not so far as the average power required to accelerate the train is concerned. This power is almost entirely inde-

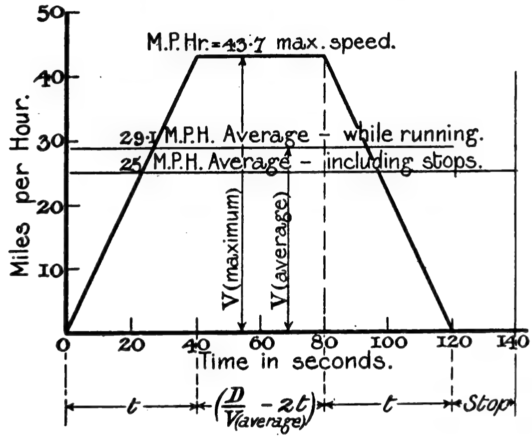

FIG. 9.—Speed and Time Curve. (Oil-electric Train.)

pendent of the instantaneous values of the acceleration, because it is directly measured by the kinetic energy stored in the train divided by the time taken to store it.

Let—

D = average distance between stations in feet.
t = time of acceleration or retardation in seconds.
$V_{av.}$ = average speed between stations in feet per second.
$V^{max.}$ = maximum constant speed attained between the stations in feet per second.
M = mass of train in tons.

The distance to be travelled at constant speed—

$$= \left(\frac{D}{V_{av.}} - 2t\right) V_{max.}$$

The total distance traversed D—

$$= \left(\frac{D}{V_{av}} - 2t\right) V_{max.} + V_{max.} t$$

$$\therefore \; t = D \left(\frac{V_{max.} - V_{av.}}{V_{max.} \cdot V_{av.}}\right).$$

The average power required to accelerate the train is obtained by

dividing the stored energy at maximum speed by the time taken to store this energy, and when reduced—

$$\text{Average horse-power} = \frac{M\,V^3_{max.} \cdot V_{av.}}{15 \cdot 8\,D\,(V_{max.} - V_{av.})}.$$

If we now differentiate the last equation with regard to $V_{max.}$ as variable, and equate the result to zero, we find that the average horse-power required to accelerate the train is a minimum when the maximum speed attained by the train between the stations is 50 per cent. greater than the average, viz., when $V_{max.} = 1 \cdot 5\ V_{va.}$, an interesting and important result.

Using the above, the size of the engine and battery required to operate a train on any given schedule can now be estimated, and it

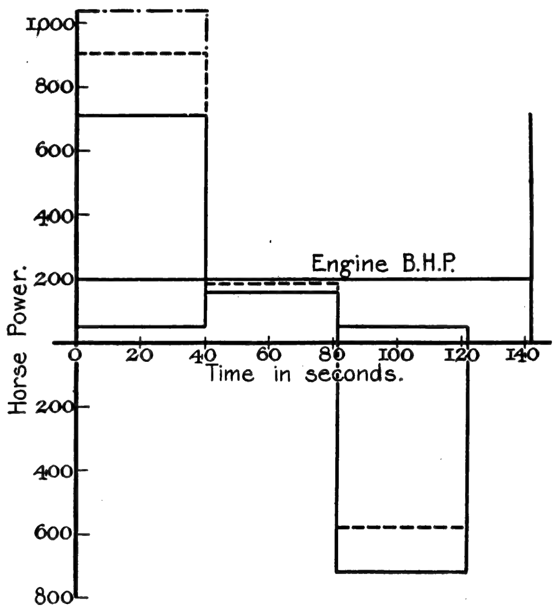

FIG. 10.—Power Chart. (Oil-electric Train.)

may be of interest to compare the cost figures for two hypothetical cases of electric traction, one on a series parallel control continuous electricity third-rail system, and the other on the system suggested above. The comparison will only be made with the direct-current system, as it is well known to be at the present time the most economical from all points of view for suburban traffic. The figures are based on a service with a schedule speed of 25 miles per hour, including stops, with 1 mile between the stops and 10 miles of double track. A 12-minute service is maintained each way for 18 hours per day, and

a 24-minute service on Sundays. A suitable number of trains to employ is 11, each consisting of two 60-ft. motor coaches and one 60-ft. trailer coach.

The cost of such a service on the series parallel system has been worked out very completely by Mr. Hobart,* and we have reproduced these figures for comparison with the proposed system in the accompanying tables :—

CAPITAL OUTLAY AND WEIGHT TABLE.

	Third-rail Direct-current System.		Oil-electric System.	
	Weight per Train in Tons.	Cost of 11 Trains, etc.	Weight per Train in Tons.	Cost of 11 Trains, etc.
		£		£
Car bodies and trucks ...	90	56,200	90	56,200
Electrical equipments ...	24	33,000	12	16,300
Engines	—	—	6	17,500
Batteries	—	—	10	12,500
Assembling	—	6,280	—	10,000
Sub-stations	—	30,000	—	—
Track and feeders ...	—	40,000	—	—
Tools, buildings, etc. ...	—	10,000	—	10,000
Totals	114	175,500	118	122,500

ANNUAL CHARGES FOR 11 TRAINS.

	Per Cent. on Capital.	Total.	Per Cent. on Capital.	Total.
		£		£
Rolling stock	8	7,640	—	20,000
Sub-stations	6	1,800	—	—
Track and feeders ...	5	2,000	—	—
Drivers' and inspectors' wages	—	4,550	—	3,500
Power	—	24,600	—	10,250
Interest on capital ...	—	7,030	—	4,900
Total	—	47,620	—	38,700
Total per train-mile	—	18·8d.	—	15·3d.

The weight of the third-rail continuous-electricity train was 114 tons, and this figure will be used in estimating the engine power and battery size.

* *Electrical Engineer*, vol. 46, p. 575, 1910.

The diagram, Fig. 10, shows a complete chart of the average power required during the various periods over the whole cycle of operations between station and station, including the standing time. The full-line curve shows the actual power required at the wheels, and the dotted curve shows the power required when all losses (except that of the battery, which is shown chain dotted) are taken into consideration. The horizontal straight line across the diagram shows the average B.H.P. required to be developed by the engine in order that the train may complete the cycle of operations in the desired time.

As the power is split up into two locomotives, the size of each engine will be 100 H.P., and each battery will be required to discharge at the average rate of 360 H.P. over 41 seconds out of every 2·4 minutes. The details of the engine and battery, weights and costs, etc., are given in the table along with the weights and costs of the electrical equipment, which includes the electric valve, motors, controlling gear, and cables.

The capital outlay and annual charges have been given in the accompanying tables alongside those of the third-rail system in order to make a comparison, and items such as the capital outlay for car bodies and trucks, tools and buildings, etc., should be common to both systems. The capital cost for the electrical equipment for the proposed system, as well as the cost of the engine, battery, and assembling, have been estimated separately.*

There is no need to go into the details of these estimates in such a paper as this, but it may be mentioned that the figures for the engine and battery are quite definite, and are those for which the makers of such apparatus are prepared to supply them.

With regard to the annual charges on the rolling stock it may be stated that the maintenance of the controller and of the third-rail has been set against that of the engine, and an entire addition has been made to the annual charges above that of the third-rail system for the battery maintenance. The latter figure has been estimated on the assumption that both batteries are completely used up per annum per train.

In conclusion, an inspection of the tables will indicate the possibilities of oil-engine electric traction in the way of reducing capital outlay and running costs. So far as can be seen from such estimates as these, the capital outlay would be reduced to approximately two-thirds and the cost of running to seven-eighths, reductions which should make the system proposed well worth consideration where capital is scarce and where there is likely to be a narrow margin between revenue and total working costs.

Discussion.

Mr. Smith. Mr. Roger T. Smith: On the first page the authors state that one of the disadvantages of the petrol-electric system is the heavy weight of the oil-engine-driven dynamo and the electric motors. I presume

* The power cost is estimated on a consumption of 0·8 pint of oil per B.H.P.-hour at 4d. per gallon, allowing for 25 per cent. idle running.

that this refers not only to road vehicles but to railway vehicles, and there is nothing like taking a particular case. A petrol-electric rail motor-car, now running experimentally on the Great Western Railway, seats 46 people, and weighs, completely equipped in running order, with its petrol and water, 14·1 tons. That is below one-third of a ton or about 700 lbs. per seat, which is less than the average weight per seat of a train on any electric railway running in this country. For a single car this is not a bad result. With regard to accumulator battery traction for road vehicles, one of the reasons for failure in the past was that up till now no such apparatus as the modified C.M.B. converter used by the authors had been available to limit absolutely the maximum output of the battery. That feature appears to be almost the most important among many excellent points in the authors' design, for no matter how badly a man may drive he cannot, with the arrangement in question, take from his battery more than a certain maximum number of amperes. Another reason for past failures has been that the battery output is so enormously increased by the great number of stops in busy traffic. As an example, two accumulator-battery motor lorries, weighing a little less than the omnibus referred to, were run over 8 miles of very busy London road, and autographic diagrams were taken of the electric motor inputs throughout their journeys. One was a lorry with two series motors and series parallel control weighing 5 tons, and the other was fitted with one shunt motor with field control and regenerative braking. On the level, during those two runs, both vehicles, loaded with 2 tons, took about 70 watt-hours per ton-mile for a non-stop run at about 10 miles an hour. That was the speed attained in Edgware Road. Over the whole journey, with constant stops for traffic, the vehicle, with the two series motors, took 141 watt-hours per ton-mile, at an average speed of 7 miles per hour, and the lorry with the shunt motor took 146 watt-hours per ton-mile, with an average speed of only 6 miles per hour. For that value of 146 watt-hours per ton-mile the energy sent back into the battery by regenerative control, amounting to 8 per cent. of the output, has been deducted. The great difficulty in experimenting with vehicles of this sort is that there are never enough of them. The whole commercial question depends on the successful maintenance of the battery, and in order to maintain batteries economically a large number of them are necessary. With two or three vehicles only the cost of properly maintaining the batteries is so out of proportion that the results are misleading, and the system is condemned. Anyhow, in the case of these lorries it was obvious that the battery system was more expensive than petrol alone. In an oil engine driving a dynamo charging a buffer battery I have much more faith, and such a combination would, I believe, be most successful with this C.M.B. converter, which would absolutely limit the output of the batteries, and also provide regenerative control as well as the other features that have been described. I do not think, however, it would be successful if designed entirely on the basis of Fig. 10. If it is assumed that Fig. 9 represents the worst case for traction—that is, **Mr. Smith.**

Mr. Smith. the shortest distance between stops—and the whole system is worked out on that basis, the vehicle is absolutely dependent for acceleration after a stop on the energy put into the battery by regenerative control during that stop, provided the engine has only the power indicated in Fig. 10. Supposing the case represented a rail vehicle, two successive signal stops in between stations would completely upset things, and before accepting such a vehicle I should ask for engine-power of at least 500 H.P., with a corresponding dynamo, instead of the 200-H.P. set shown in the diagram, so that whatever the conditions of traffic might be, there would always be a certainty of having enough power to go on charging the batteries, even with, say, three signal stops and no chance of full speed in between stations 1 mile apart.

As an example of the difficulty of meeting all sorts of service conditions, a recent test of the petrol-electric rail motor-car referred to above may be mentioned. On a fairly hilly section, with stops half a mile apart, the input into the two series motors geared to the axles was 55 watt-hours per ton-mile in order to run at an average speed of 13 miles per hour, whereas the same vehicle ran over the same road with a distance of 3 miles between stops with an input of 45 watt-hours per ton-mile for an average speed of 21 miles per hour. That shows the decrease in speed with a slight increase in power when the stops were half a mile instead of 3 miles apart. The car with the buffer battery absolutely depends on the condition of charge of the battery to get its acceleration, but if the state of the battery did not allow of rapid acceleration the engine on the car could still move it, which is a very great advantage. I cannot accept all the authors' weights and prices given in the tables for the single railway car, but the arrangement should work well provided the railway happened to have an existing organisation for maintaining batteries. The whole question of success depends, as already stated, on the battery maintenance. No battery maker could maintain batteries on a railway at several different depôts scattered all over the length of line. I have not been able to examine all the figures for the oil-electric train which is to compete with the suburban electric train, but I cannot accept some of the weights and prices given on page 118 of the paper. For the oil-electric train the weight of the electrical equipment is given as 12 tons, while that of the pure electric train is given as 24 tons. Those two trains weigh about the same, they have the same schedule speed, and therefore they must have the same motors geared to their axles. I have taken out for six electric railways the average percentage of motor weight to that of the total electrical equipment and find it 77 per cent. Both the motors being the same, it is obvious that at least 6½ tons must be added to the oil-electric weights on this account. In addition to that the Board of Trade would insist upon air brakes as well as regenerative braking, and the air-compressor equipment weight would have to be added. Unfortunately the whole principle of the system is rather in the hands of the Board of Trade. In order to work the system it is essential to use

electric braking, and if the Board of Trade said that air braking must be used the battery could not be charged by regenerative control, so that the permission of the Board of Trade would have to be obtained before the system could be a success. Further, the 500-H.P. engine (instead of a 200-H.P. engine) and the corresponding size of dynamo, would add, with the 6½ tons mentioned above, about 16 tons to the weight given in the paper for the oil-electric train. Then the battery may or may not want to be larger, but I think it is much more likely to weigh 16 tons (instead of 10 tons) in order to cope with all conditions. These additional weights and the corresponding additional money would, if my view is right, take off a good deal, if not all, the advantage claimed over the electric train. In spite of this criticism of details, I want to congratulate the authors very heartily upon the attractiveness of the principle and the way in which they have worked this out. In connection with the formula given on page 117, the condition for minimum horse-power during the acceleration period is very neatly shown and is, of course, perfectly correct. But I wish to sound a note of warning in regard to the use of this result, because what we want to know in general is not the minimum horse-power during the period of acceleration, but the minimum horse-power from start to stop, which is quite a different thing. If the horse-power is to be a minimum from start to stop, in general the average speed must be as nearly equal to the maximum speed as it can possibly be. The value of the conclusion arrived at by the authors only comes in where the distance between stops is so very short that almost the whole period is taken up in acceleration and in braking. Mr. Smith.

Mr. W. A. STEVENS: I cordially agree with the authors' remarks on their regenerative control for battery vehicles. I have ridden on one of their vehicles, and can vouch for its smooth running and ease of control. As a battery vehicle it will be hard to beat. It is well adapted for running in congested traffic, and for crowded city traffic it leaves little to be desired from the passenger's point of view. I should like to make a few observations on some of the points put forward in the paper. On page 93 the remark is make that the defects of the first system (an engine-driven dynamo supplying energy to a motor or motors connected to the driving wheels) are evidently the large weight of electrical transmission gear and the low efficiency. I should like to point out that the weight of a satisfactory electrical transmission is under 10 cwt., and the weight of the battery and electrical equipment in the proposed petrol-electric vehicle is 13 cwt. 1 qr.; the actual efficiency of transmission being probably in favour of the vehicle without the battery. On page 102 I note the weight of the back axle with cardan shaft is 4 cwt. 2 qrs. This strikes me as being very light. The weight of the back axle of the latest B type L.G.O. vehicle is considerably over 8 cwt. I agree with the position of the battery, with accessibility of connections, and facility of removal, and I consider the general arrangement in this direction very satisfactory. Taking the chart of discharging currents on page 105, it will be seen that the actual value of regeneration in charging Mr. Stevens.

Mr. Stevens.

the battery is quite small. With heavy roads this would practically disappear. I agree that this power of regeneration is very valuable in controlling the vehicle, and am fully of opinion that a battery vehicle such as has been described will be of great use for carrying heavy goods for railway and dock work, in addition to general purposes where no long continuous runs are required. In this field I consider the heavy battery vehicle has a great future. In the proposal for a petrol-electric vehicle I should like to make a few friendly criticisms. On page 107 it is proposed to reduce the battery to one-fifth of the capacity, and by adding a 9-H.P. air-cooled petrol engine to drive the electric valve to keep the battery charged sufficiently to supply the electric motor for long continuous runs. I am not clear if the engine is to give 9 B.H.P. or to be capable of driving the electric valve when giving an output of 9 E.H.P. I assume the latter, in which case the power of the engine should be 11 B.H.P. In my opinion, the engine power is largely under-estimated for the following reasons: Taking the most favourable conditions of efficiency, the engine running at full load, driving generator, supplying the electric motor with the battery floating, the loaded vehicle weighing 6 tons, running at 12 miles per hour on level roads varying from asphalte to macadam. According to Molesworth, road resistance varies from 35 to 90 lbs. per mile, according to condition of roads. The figures given by the "Automobile Engineer Year Book for 1912" vary from 18 to 52 lbs. per ton. Taking the average of 35 lbs. per ton, the power required to run a 6-ton vehicle 12 miles per hour will be $35 \times 6 \times 1{,}050 = 6{\cdot}7$ B.H.P. In many cases, even on level roads, it will be twice this. The actual B.H.P. applied to the road wheels by 9 E.H.P. acting on the electric motor (assuming the efficiency of the electric motor at 88 per cent. and that of the wormgear at 90 per cent.) will be 7·1 B.H.P. This gives a margin of 4 E.H.P. for charging the battery, accelerating, overcoming wind resistance, and possible brake friction. On referring to Fig. 5, it will be seen that little help can be hoped for by regenerative charging, and, with the system proposed, regeneration will be a positive disadvantage, as, on going downhill, the consequent acceleration of the generator will cause the engine to cut-out when the battery is badly needing a charge. Turning to the table of detailed weights of the proposed petrol-electric vehicle, I note the first item gives the weight of the engine, including silencer and full petrol and oil tanks, as 1 cwt. 3 qrs. = 196 lbs. Assuming the weight of petrol and oil tanks as 12 lbs., the silencer as 6 lbs., 10 gallons of petrol as 80 lbs., and 1 gallon of oil as 9 lbs., this gives a total of 107 lbs., leaving less than 90 lbs. for the weight of engine with magneto, carburettor, and flywheel, with necessary cooling fans, and this engine must run for 15 hours a day for at least 300 days per annum. I trust the authors will forgive my criticism, which may have been made under a misapprehension of the details given in their paper. Although not a railway man, I should anticipate great success in railway work, owing to the comparatively larger battery and engine, also the small running resistance.

Mr. A. H. SEABROOK: I would like to make a few remarks from the electric supply point of view. From this point of view the paper is a most important one. The authors touch on the question of tariffs, and suggest that energy should be supplied at the rate of ½d. a unit. Considering the class of load and the time of the day at which it would be supplied, I think ½d. per unit is quite a reasonable figure to charge. Taking a minimum demand of, say, 100,000 units a year, a charge of ½d. per unit, say, between midnight and 6 a.m. and ¾d. during the day, and no supply given during peak, ought to go a long way towards encouraging the general use of these vehicles. At present, so far as London is concerned, practically none are in use. This is really a most extraordinary thing. I do not understand why in other countries these electrical vehicles are used extensively, and are run for commercial and other purposes in considerable numbers, and are on the increase. In St. Louis there are 450 of these vehicles, and the electricity supply undertaking has 36 for its own use. I do not think, at any rate I have never heard, that there is a single supply undertaking in the whole of Great Britain which can boast of possessing a single electrical truck. Denver has 800 electrical vehicles, and the Denver Supply Company has 9 for its own use. Cleveland, with a population of half a milion only, has 1,800 electrical vehicles. Chicago has 2,400 electrical vehicles, and a large number are used by the Chicago Edison Company. A little place like Rockford with 40,000 inhabitants has 170 electrical vehicles, and Dayton has 85 vehicles. I do not agree at all with the explanation or excuse put forward that the petrol vehicle is better, and that it has been allowed a bigger headway. I think those are explanations which are unworthy of the name of excuses, and they are not worth considering, because the petrol vehicle has had precisely the same opportunities in other countries as in this country—in fact less opportunities in this country if anything. I think the great point is that the electric supply authorities abroad have taken this business under their own wing and encouraged it and co-operated with the manufacturers. Here in this country, if anybody brings out a new thing the whole burden of doing so seems to be put on the manufacturer; there is always the tendency to make him stand the whole of the expense of introducing it and developing it. That is absolutely unreasonable in my opinion. The people who supply the current for all sorts of electrical purposes, including vehicles, make far bigger revenues and profits proportionately than the people who make the apparatus, and they should certainly assist in the development and use of those articles. The driving is quite extraordinarily easy in this particular C.M.B. control. I had the opportunity of driving one of these vehicles at Chelmsford. The authors say that they are fool-proof, and from personal experience I can assure the members that they are entirely so. Coming back to the question of co-operation between the electric supply undertakings and the manufacturers, the companies, to my astonishment, are really rather worse than the local authorities on this question. They are all as bad as can be, but there is less excuse

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for the supply companies to be less forward in this matter. With municipal authorities we always have the expert who can get elected to the Council, and who, though not noted for brilliance of intellect, is sometimes able to sway the Council in the event of a snap division. They call it speculating with the ratepayers' money, but then they should have thought about that before they went into the business at all. This seems to me to be a question that could very well be submitted to the proposed Commercial Section of the Institution to see whether they cannot do something, by knocking people's heads together, towards introducing this business on a commercial scale in the country.

Mr. Thomson.

Mr. HEDLEY THOMSON: On behalf of Mr. Thomas, who is at present in South Africa, I should like to thank the authors for their reference to the Thomas electrical transmission gear. Electrical systems of transmission are beginning to receive some recognition, and, as evidence of this, the Royal Automobile Club has just granted the Dewar Trophy to Mr. Thomas for two trials which were carried out last year with a lorry and a touring car, under R.A.C. supervision. In one of these trials the ton-mileage obtained was 19 per cent. better than any previous R.A.C. record with gear-driven vehicles, the result being 68 ton-miles per gallon of petrol. I should like to correct the authors' statement that a battery is necessary for reversing with this gear; that is not so. Many of the vehicles already made with this transmission have been run without using a battery, although in most cases it is found convenient to fit one, as it can readily be charged when the vehicle is running on top speed, and so provides an ample supply of current for lighting and self-starting. The three systems adopted for reversing are: (*a*) A purely mechanical reverse; (*b*) purely electrical, without battery; (*c*) by the use of a reversible engine. The last-named method is found most convenient for heavy work. With the information before me I am hardly competent to discuss the technical details of the system put forward in the paper, but there are one or two points of interest about which I should like to make a few remarks. The two outstanding features of the paper to me appear to be, first, the very small weight to which the authors have been able to reduce their electrical equipment, and secondly, the ingenious method whereby regenerative electric braking is made possible. Regarding the weights, in Section I., it is stated that the electrical equipment complete for a bus weighs 7 cwt. I think it would be interesting if we knew how that weight is apportioned, and were given the weights of the several units comprising the equipment. Then with regard to the braking, in stopping a skid it is absolutely necessary to have means of free-wheeling. I presume the authors have made arrangements for this effect to be obtained with certainty and speed in case of emergency. A considerable portion of the paper is devoted to the question of working costs. I do not wish to criticise the actual values of the figures given on page 106, but some comment might be made upon their relative values. In the case of the electrical vehicle, the "chassis main-

tenance" is put down as 0·10d. compared with 1·00d. for the petrol vehicle. I think there must be some error in these figures. Although the wear and tear of the electrical vehicle will certainly be less than that of the petrol vehicle, the chassis maintenance costs would surely not be reduced by as much as 90 per cent. Similar criticism might be made as to the item "Washing and preparing for running." In the case of the electric vehicle, this is put down at 0·17d., and for the petrol vehicle 0·90d. If we accept the latter figure, then a London motor bus, which runs 100 miles a day, costs as much as 7s. 6d. each morning for preparing it for its day's work! In conclusion, I hope the authors, and also the firm with which they are associated, will receive all the encouragement and help they deserve in carrying out difficult pioneer work of this kind. There is a friendly rivalry between the firm with which I am associated and theirs, and I think perhaps the greatest compliment I can pay them is that we should very much appreciate being able to obtain for use with the "Thomas" equipment the very light motors which the authors have so successfully designed. Mr. Thomson.

Mr. H. E. WIMPERIS: We are getting to the point, particularly in railway suburban work, at which a fairly high schedule service, frequent stops, and the short distances between stations have caused a tremendous loss of power in the braking. I believe now that, on the shortest runs on some of the tube railways, we have got to the point at which the amount of power used in propelling the train is actually less than that used in grinding up the brake blocks. That is a serious situation, because it means that if we are going to reduce the distance between stations we shall have still more and more this tremendous waste of power—power that is not at all helping us to carry out our purpose, which is to get from place to place. Fig. 10 shows the kind of thing that is going on. Those large rectangles at the beginning and end of the journey show the power that is used simply in starting and stopping, whereas the power that is taken for ordinary running is quite small in comparison. Where we have fairly large distances between stations, regenerative control is not worth thinking about, but where we have frequent stoppages it certainly is. On railways we have got to the point at which it has seriously to be considered. With road transport I do not know that we are quite in the same position, because, as has been pointed out by a previous speaker, on a railway the resistance is only about one-third of what it is on an ordinary road at the speeds usual in each case. That means that a much larger amount of power is necessary for getting from place to place, and that therefore the losses in grinding up brake blocks are not as great in proportion. Mr. Wimperis.

The authors have divided the subject into three parts, and it would perhaps be suitable for me to deal with it in the same way: First, electric vehicles; secondly, petrol-electric vehicles; and thirdly, an oil-engine electric system for suburban railways. I think that in connection with the electric vehicle, the really important point is the success that has been attained in making the whole of the machine as fool-proof as a previous speaker noted it to be. On page 99 the authors refer to the

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useful braking effect of the regeneration, and say that "This torque is arranged to be of such a magnitude that it holds the vehicle on a comparatively steep downward gradient, and yet has not sufficient power to cause the vehicle to start backwards on the level." That I do not quite understand, because the torque necessary "to cause the vehicle to start backwards on the level" would only be about the order of 45 lbs. per ton at the most, and if it will only exert *that* amount of torque on a hill, it could stand a gradient of no more than 1 in 50, which cannot be considered "comparatively steep." On page 100 the authors speak of the acceleration or retardation being proportional to the rate of forcing down or raising the point. I wonder if that is really what they mean, or whether they mean that it is proportional to the amount which the pedal is forced down. If it is proportional to the rate at which the foot is moving it is a very unusual arrangement. In the curve in Fig. 3 a torque curve is shown for the battery vehicle characteristics. That is

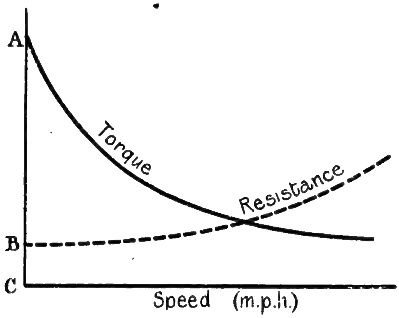

FIG. A.

the kind of torque that we need on a moving vehicle. The authors have not stated what acceleration they get with this at starting—which is an important point; but taking that diagram, if the normal speed be about 12 miles an hour, the starting acceleration would seem to be something like 7 ft. per second per second. The authors' torque curve is generally of the shape shown in Fig. A. If we plot on the same diagram the total resistance, air and road, it will give a curve similar to that shown dotted, and the crossing-point is, of course, the point of maximum speed on the level road; that is to say, when there is a torque just balancing the resistance (both being plotted to the same scale). When we are starting and our speed is nothing, our resistance is only about the amount shown at B C, and we have the torque equal to A C. The surplus torque, A B, is therefore the torque that produces acceleration, and from the scale of the authors' diagram it seems to me that the acceleration at starting would be about 7 ft. per second per second. I do not know whether the authors have made any measurements of starting acceleration. If they have, and if they found anything like 7 ft. per second per second, their passengers must have experienced some-

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thing very different from what they are accustomed to on an ordinary motor bus, where the initial acceleration is only about one-third of that amount. It is interesting to contrast this curve with the torque curves of the petrol engine, where the torque law is really a series of stages depending upon the number of gears used, and is much more ragged than an electric torque curve.

On page 106 the authors give a few figures for the energy consumption with their electric vehicle, and find that 88 watt-hours per ton-mile are being used. It so happens, as I have pointed out elsewhere, that there is a convenient rule that 2 watt-hours per ton-mile are the equivalent to 1 lb. per ton. Within a trifling error these two things may be said to be exactly equivalent. Now if we measure the total resistance to motion for a vehicle of this type, at about 12 miles an hour, including any internal frictional resistances of road-wheels, etc., we shall probably find it to be not less than 45 lbs. per ton. If we double this figure we have 90 watts per ton-mile as being the dynamical equivalent of this amount of resistance, and even if our electrical gear had 100 per cent. efficiency, we must needs have 90 watt-hours per ton-mile. The authors' measurement comes singularly near this—viz., 88 watts per ton-mile—in fact, it is so near that I wonder whether they have measured it quite rightly, because there must be some loss due to the efficiency not being 100 per cent. even in such admirable apparatus as they have described to us. The rule mentioned above will often be found to be of use in checking measurements of this kind. Coming now to the petrol-electric system, a point that I think it is important to raise is that the authors speak on page 110 of the 9-H.P. engine being run air cooled only. If that is going to be possible, why is not the ordinary 9-H.P. motor-car air cooled? It runs at a much higher speed through the air, and is therefore in a much better position to get cooled than the slower vehicle, and I would like to have some explanation from the authors as to why they think it is more feasible with their apparatus to run a 9-H.P. engine with air cooling only than it is under ordinary circumstances. In the further part of the paragraph they say that: "The load factor being approximately 100 per cent., the consumption of petrol will not be more than half that of the ordinary petrol vehicle." The ordinary petrol vehicle of this type and weight runs about 45 gross ton-miles per gallon of fuel; and the fuel being petrol (of known calorific value), it is quite simple to deduce the average thermal efficiency of the engine, which comes out at 10 per cent. in this case. I agree with the authors that they probably could double that efficiency, due to improvement in the load factor. An ordinary petrol engine ought to give quite 20 per cent. efficiency on a long run at full load, and that being so they ought to get instead of 45 ton-miles something like 90, which would correspond to 15 miles run for each gallon of fuel. I worked through this calculation before discovering that on page 112 they had themselves made an estimate of 14 miles per gallon, but it does not appear from their paper that any actual measurements have been made which might, or might not, confirm these

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predictions. If they have made any measurements it would be interesting to learn what result was obtained. The next point I would like to refer to is connected with Fig. 9. The authors show a starting acceleration of $1\frac{1}{2}$ ft. per second per second, but I am astonished to see that they show the braking to the same extent. That is very widely divergent from current practice. Current practice with electrical trains shows that although to start at $1\frac{1}{2}$ ft. per second per second is not out of the way, to stop at $1\frac{1}{2}$ ft. per second per second, intentionally at any rate, is almost unknown. Electric trains and steam trains stop at anything from 4 to 6 ft. per second per second, some three times as great a rate. Therefore if that curve were to represent modern practice the second line would have to be three times as steep as it is. Moreover, if their intention really is to brake only to one-third of the ordinary extent, it is obvious that the train will have to run three times the distance before it does stop, and I do not think they will be getting anything like as good a speed schedule as they would obtain if they conformed to what is more customary. I suggest to them that they should brake at something like the rate that is customary now, about 4, 5, or 6 ft. per second per second, and make an effort to start at something like the same amount. This sounds a startling suggestion, but it must be borne in mind that what affects passengers is not a high acceleration but a rapid increase in acceleration. It is the rate at which we get up acceleration, the rate of increase of acceleration, that matters. If the acceleration could be increased gradually from zero up to 5, 6, or even 7 ft. per second per second neither passengers nor stock would suffer.

Mr. Robson.

Mr. W. E. Robson: There are, I consider, two features which are essential in an ideal vehicle driven by any engine or electric motor for use, where starting-up takes place at frequent intervals, and where a fairly high schedule speed is required. The first is that during acceleration there should be a graduated supply of power to the road-wheels, so that the pull on the vehicle is constant while the speed increases, and this should be given without waste of energy. The second is that all energy not used in overcoming tractive resistance should be recoverable, *i.e.*, the kinetic energy of the moving vehicle at top speed should be utilised. The authors have tackled the second feature in what is essentially the most straightforward way with electric appliances; they have the courage to use a battery as an energy reservoir, they draw from it to supply energy to overcome tractive resistance and to give kinetic energy to the vehicle, and they restore as much as possible of the latter. They have also, to a certain extent, fulfilled the first requirement. Dealing with the first section of the paper the disadvantages of the petrol vehicle are very fully stated, and they may be considered as the same for steam vehicles. It is interesting to note that electrical engineers have one of their greatest friends of activity in devising means for neutralising the inherently bad characteristics of the mechanical engineers' engines; if these charac-

Mr. Robson.

teristics were other than they are there would be little use for batteries, boosters, electric traction, etc. The advantages of battery traction for city work are not understated. On the test figures on page 106 the range of bus per charge is 50 miles, but city conditions will be much worse than on this test. There will be a much larger percentage at high amperage from and into battery, and the capacity of the battery will be less than there stated. (The authors have taken the capacity as 500 ampere-hours, which is really on a 5 hours' basis and must have been less when the discharge curve has such large periods at 150 amperes and over.) The possible reduction in capital, rates, rent, and taxes, etc., are more or less debatable. With omnibuses the better lighting and smoother running in themselves will not create a traffic, unless the speed of service is better. I should like to compare the figures given by the authors for the savings in running costs for their proposal as against those given for previous battery buses. Previous buses consumed something over 1 unit per mile—say 2 units for charging. Their bus used 0·53 unit per mile, and they take 1 unit for charging. I think for city traffic these last figures must be increased rather greatly; but, letting them stand, their bus then costs, at ½d. per unit, which they have taken, ½d. per mile less than previous buses. This would bring the cost per bus-mile for the previous types to 4·1d. as against their 3·6d. This still gives the old type an advantage over the petrol bus figures of 4·7d. The only other ways in which they would have a commercial advantage would be that the saving in weight by their system would allow more passengers to be seated, and that the maintenance charges for battery would be less. I do not think the first applies, for there was not much overcrowding on the old buses, and for the reasons given it would not be very safe to assume the latter. With regard to the American electric vehicles I think that these are mostly electric runabouts, and in any case the cost per vehicle-mile for pleasure working is rarely the determining feature. With regard to the system proposed, the great feature of originality in the drive is the employment of the C.M.B. auto-converter in place of a double machine—*i.e.*, a motor booster set—otherwise the system is a modified Ward-Leonard system. Any advantage gained is in the saving of weight, but this is only trivial, as the whole electric equipment with motor is only 7 cwt. The partial transformation by their electric valve of half the power supplied to the motors is quite comparable with what is possible with a motor-booster set. In the motor booster greater variation of voltage is possible. As an example, in the Electric Railway Engineering Laboratory of the City and Guilds Engineering College, a system to my design enables us to deal with 200 k.w. of power from main supply with a 40-k.w. booster set. We are able with this set, taking supply at 400 volts, to have definite direct-current voltages from 50 to 500 in eight steps without resistances, and alternating-current voltages from 30 to 3,000 at any frequency from 25 to 50 volts. Dealing with the method (*c*) used by the authors, the claim that the torque-speed characteristic is similar to that of a series motor, if I

Mr. Robson. understand the description aright, is surely incorrect. In a series motor up to full voltage for any given armature-current the torque remains approximately constant. In the authors' system from 0 volts on driving motor up to battery volts across motor, the winding E is assisting D, but with gradually reducing effect, until when volts on motor-battery volts only D is effective. Then from battery volts up to battery plus booster volts across motor, E is acting against D with gradually increasing effect. This means that from O speed up to full speed the field strength of the driving motor is being gradually reduced, if the current through C is maintained constant, and the action of the series coil H on the booster obviously tends to do this. It would seem, therefore, that the torque characteristic is really rather worse than that of a shunt motor during acceleration. In the characteristics (Fig. 3), given on page 102, these are given as being for "full on," but assuming this means full + excitation of the part B, I take it that the current taken by the motor C is such that winding H overpowers F to a great extent. This means a strong flux on C, because effect of E is either to help D, or not to reduce it greatly. The torque produced will then give a high acceleration, but as speed increases the torque and acceleration at once fall, and there is no means of preventing this. The form of the acceleration-time curve is thus a bad one. If a high average acceleration or deceleration is required, and comfort to passengers ensured, it should be arranged that acceleration at first increases and then decreases, and not *vice versâ*. The bus is claimed to be able to get up to full speed from stop, or down from full speed to stop in 1½ to 2 bus-lengths. Taking the bus weight as given loaded, 118·5 cwt., and full speed as being 13 miles per hour, the stored energy is 74,500 ft.-lbs. The average speed during the acceleration or deceleration is 6½ miles per hour, or 9½ ft. per second. The bus-length, as scaled from drawing, is about 20 ft. To cover two bus-lengths—40 ft. —at 9½ ft. per second needs 4·2 seconds. The average acceleration during that time is 3·1 miles per hour per second. The average horse-power during that time is 32·3—that is, 24·1 k.w. The average current from battery during that time is 400 amperes. These are only average values, and if, as I have shown, the acceleration becomes less as speed increases, then the maximum values must greatly exceed these, especially when the transformation losses are allowed for. I should like to have this explained, for it appears to be impossible to get more than 300 amperes from the battery according to the curves. It is of importance as bearing on the use of the bus in city work where emergency stops and starts are necessary, for the capacity in ampere-hours and the maintenance must depend in a great measure on these maximum demand periods. From the design of the bus it would seem that well over half the weight of the bus is on the front wheels, the drive being on the back. It would appear, for the acceleration to take place in two bus-lengths, that the ratio : (weight on drivers) ÷ (tractive effort necessary for the acceleration) is only about 3. This, I take it, is too low as a working proposition, and it would be preferable for this

reason to have the battery under the floor of the bus. This is obviously not such a handy place. By plotting torque against current from the curves on Fig. 3, I find that the torque in ft.-lbs. over the greater part of the range of current is equal to $1{\cdot}14\ C - 60$, where $C =$ amperes. This is the same form as a shunt torque-current characteristic. The objections to limit-switch operation in electric railway working have frequently been pointed out, and I fear that a battery system must either labour under a disadvantage of only moderate acceleration if using preventive measure equivalent to limit switch, or else must be large in capacity so that maintenance is not excessive. If, as the authors state, they have a definite maintenance figure from the battery makers for a battery for use on their system, and city operation conditions are included in that guarantee for a long term of years, then the regenerative control should give it a commercial success. Mr. Robson.

In Section II. it would appear that the authors recommend the battery system in preference to the petrol-electric where charging stations and battery makers are within range, but outside of this they recommend a petrol-electric system. Making a comparison, however, between the tables on pages 105 and 113, and allowing 0·2d. per bus-mile for insurance in the latter, it appears that the petrol-electric costs per mile are 3·35d., as against 3·6d. for the all-electric. In face of this, how do the authors give the preference for city working to the all-electric, especially in view of the lighter weight for the petrol-electric? A fair claim can be made for a single motor-coach train on the authors' method for a system where traffic is very light and the service is infrequent, but it would require great gains to compensate for the complications of a multiple-unit control where each motor coach has electric motors, a motor booster, a battery, and a petrol engine, as against electric motors only on a third-rail system. Their saving really depends on the regeneration, and the objections against limit switching apply here. Since electric motors—that is, direct-current series, not alternating-current single-phase—can stand excessively heavy overloads for short periods, any development of a regenerative control without extra motor converters, allowing energy to be returned to line, must be greatly superior to the system proposed in the paper.

Mr. A. M. TAYLOR (*communicated*): The continuous failure of all attempts to introduce accumulator traction in this country makes it essential on our part to examine very carefully any fresh proposals. I have unfortunately to disagree with the authors both as to the energy required and as to the charge for battery maintenance. On page 106 the output of the battery is given as 530 watt-hours per bus-mile. Now the mean of a large number of tests published in the *Engineer* a few years ago gave 44 lbs. per ton as the tractive force on a macadam road in good condition. At $12\frac{3}{4}$ miles per hour this is almost exactly 9·0 B.H.P. developed at wheels. Taking efficiency of gearing as 95 per cent., that of the motor (at $\frac{1}{2}$ load) as 85 per cent., that of the "valve" as 83 per cent. (as to which see later), I find that 10 k.w. are required at the battery. But, according to the author's figure (530 Mr. Taylor.

Mr. Taylor. watt-hours), only 6·75 k.w. are required. We must, therefore, add practically 50 per cent. to the authors' figures; from which we find that, instead of running 50 miles with one charge, the bus will only run 33 miles. In order to do 50 miles we must either increase the weight of the battery by 50 per cent. or reduce the life (which depends on the number of discharges) by 33 per cent. In other words, we must increase the maintenance charge from 2d. per bus-mile to 3d. I have arrived at the loss in the valve in the following way: Current from battery at 12¾ miles per hour = 120 amperes (page 106); E.M.F. of battery = 53 volts; current through motor = 50 amperes (authors' curve, Fig. 3); E.M.F. across motor (Fig. 2) = 105 volts; kilowatts across motor = 5·25; kilowatts across battery = 6·36; ratio = 5·25/6·36 = 83 per cent. = efficiency of "valve." The efficiency of the valve for other speeds, derived in the same way, is as follows: 0 miles per hour, 54 per cent.; 1·5 miles per hour, 81 per cent.; 3 miles per hour, 95 per cent.; 8 miles per hour, 90 per cent.; 12¾ miles per hour, 83 per cent. Next, as regards the maintenance of the battery, I am not quite satisfied that 2d. per bus-mile is a safe figure, even if their figure of 530 watt-hours were proved correct; and I think it should be 2½d.—*i.e.*, 3·9d., if the measurements of power be also found to be wrong. This figure is based upon its not being safe to count upon more than 7,500 miles per renewal, nor upon a life of more than 150 discharges. I understand that a certain well-known traction cell fell off in capacity by some 40 per cent. with about this number of discharges; and, if we are to assume that the capacity is to be held up to 100 per cent., we ought even to go below the 150 discharges assumed. Even if a battery company offers better figures it is easier for them to take risks than it is for the exploiters of the new system, and they (the battery people) can always close their contract if they find it does not pay to continue, whereas such a failure spells ruination to the promoters of the scheme. I also base my figures upon its being necessary to pay, for new plates for the cells, something like 75 per cent. of the original cost of the battery; this figure, however, to include the staff required for the changing of the batteries in the vehicles and the charging-up of the batteries in the garages, and, generally, of keeping them in order. The output, per weight, of the cells is particularly good, and I would be glad to know the name of the makers. From the point of view of cost of charging the battery, it is also impracticable to expect central station people at present to give current during the daytime at ½d. per unit, and I therefore think that the latest Edison cell, which can wait for its charge, even when quite exhausted, for many hours without injury, would have an advantage over the lead-plate battery. The authors' figure of ½d. per unit is too hopeful for an average figure—at present anyhow.

Mr. Burnand. Mr. W. E. BURNAND (*communicated*): The authors have developed a scheme of regenerative control which promises to be a valuable asset to the subject under discussion. Complete regenerative control, as in this scheme, renders battery propulsion practical in many cases where

Mr. Burnand.

otherwise it would not be commercially possible. I think the comparisons between the electric and mixed systems, and the petrol vehicles, are unfair to the latter, and that page 95, and parallel columns on pages 106, 112, and 114, arranged by the petrol man, would look different and show probably a balance on the other side. Most likely an intermediate value is the correct one. I should estimate the balance favourable to the electric at about one-quarter that assigned by the authors. Worm-drive, where efficiency of transmission is so vital as in the electric vehicle, might with advantage be replaced by silent chain. The engine plugging away at full power all the time is not specially adapted for air cooling, and should be heavier than an ordinary motor-car engine of equal power, which averages only about one-third of its maximum in ordinary use. The necessity for this increased weight has been quite a common experience in motor-boat work when the conditions are analogous. For these reasons the advantages in favour of the electric or mixed self-contained systems are not so overwhelming as to ensure their adoption to the exclusion of others even under the conditions assumed by the authors. All the same, there is a place for them. Curve 5 is hardly fair to the authors' system ; there is no regeneration to speak of, and probably a plain series motor would have made a slightly better showing owing to the absence of the converter losses. The speed-torque curve (No. 4) in Fig. 3 is not what is usually desired—it falls far too quickly before approximately full speed is attained. The converter control arrangement can, however, be altered to deal with this. Away from the self-contained idea I think the conditions are much more favourable. Take the case of the London Underground. The waste of energy is too painfully apparent to be considered by an engineer with comfort. Consider now the trains equipped with complete regenerative control, for instance, as shown in Fig. 1 of the paper, but leaving only a short length of third-rail at each stopping-place and a little way beyond. Some important results follow : for instance, the batteries being relieved of most of the work of acceleration, can be smaller. Having a refresher or charge-up every minute or so, they can be made smaller still. Having only to propel the train a minute or two, even if there is a stoppage between stations, very few units are required out of the battery. This renders possible a battery of plain thin lead-plate, with only a small amount of preliminary forming. This battery appears to me to get over most of the troubles of the usual style. The maintenance is only a fraction of what is necessary with the usual batteries. The first cost obviously is very much less due to its less weight and cheapness of manufacture and materials. The surface available with this battery and the nature of the surface permits of the requisite acceleration without damage to the battery, in the case of stop between stations. The same things permit of the battery taking a charge in a matter of seconds, sufficient to carry easily from one station to another, the full capacity of the battery, of course, being several times this. Thus, by the combination I propose—namely, regenerative control—a charge-up or refresher at each convenient stop,

Mr. Burnand. and a non-pasted lead-plate battery, which is comparatively inexpensive in first cost and upkeep, the following can be gained: a reduction of nine-tenths of third-rail or trolley wire construction; a reduction of about a third in energy used; avoidance of difficulties at crossings, and lights bobbing out, and most of the wear and tear due to mechanical braking eliminated. There are, of course, many details, and some difficulties in its application, but nothing that cannot be overcome by probably much less thought and labour than has been expended on most existing systems. The same arrangement obviously applies to street tramways, and would put a different aspect on the stud system. It is also applicable to vehicles not running on rails, and, although the conditions are not quite so favourable, I think they are in many cases more so than for self-contained arrangements in first cost and costs of power generation for fairly dense traffic.

Mr. Cooper. Mr. W. R. Cooper (*communicated*): In the very interesting arrangement for an accumulator bus described by the authors it is difficult to see where a very marked increase in efficiency above previous types is obtainable except when the bus is accelerating, chiefly from rest. The arrangement is equivalent to a battery with a reversible booster, and it is during the periods when the controller would be in the series positions (*i.e.*, with the booster opposed to the battery) that the chief gain in efficiency must take place. When the bus is running freely, corresponding to the usual controller position with no resistance in circuit, the efficiency must be less than with a simple battery of accumulators, because half the energy is being transformed by the booster. This would be the condition during most of the run recorded in Fig. 5, and therefore I do not understand how such a low figure as 88 watt-hours per ton-mile was obtained unless everything was in exceptionally good trim and the roads were very good. Of course there was a certain amount of regeneration, which would improve the figure, but this part of the energy was only a small proportion of the whole.

Turning to the figures in the paper it would be interesting if the authors would give the weight of the converter. It is not quite fair to compare their battery of 19 cwt. with one of 2 tons as used on previous accumulator buses. The weight of the converter should be included, and any gain by omitting the usual series-parallel controller should be set off against it to get a true comparison. It is also difficult to understand the statement that previous accumulator buses failed because they had not sufficient passenger accommodation: the electrobuses carried 34 passengers, the same number as the bus described by the authors. The authors' bus appears to be more lightly built. The "Electrobus," from published data, weighed, fully loaded, 7 tons 12½ cwt., whereas the authors' bus weighs 5 tons 18 cwt. The smaller battery then should be capable of running a considerably greater distance than would be implied by the direct ratio of its weight. What one would like to know is how a run on the authors' bus with a 19-cwt. battery and the ordinary series-parallel control would compare with the result shown in Fig. 5. Would it really be

much inferior? The authors claim a radius of 50 miles, which is higher than the figure usually attained hitherto, but I believe I am correct in saying that an "Electrobus" made a trip from London to Brighton, a distance of 52 miles, on a single charge two or three years ago. In order to run such a distance as 50 miles, however, the authors use the total capacity of their battery, and this would be uncommercial. It has been generally recognised that for success in accumulator traction the battery must not be worked to more than, say, three-quarters of its full capacity, and there must also be a margin for the varying state of the roads. For town working the authors' arrangement would, of course, show to greater advantage, but in the table of comparative costs it seems doubtful (taking the authors' figures for efficiency in Section I., sub-section 3), that the energy per mile at the charging station would be so low as one unit, considering that the test run on top speed in the country required 0·53 unit per mile from the battery. The figures for chassis maintenance and washing seem unduly low for the electric bus. Mr. Cooper.

Mr. H. N. DUTTON (*communicated*): With special reference to Section III. of the paper it may be of interest to say a few words regarding the progress of the petrol-electric system on the Continent as engineered by the Westinghouse Company. This company has supplied a number of cars working on the petrol-electric system to various railways, the two chief installations being the Arad Csanad Railway in Hungary and the Oosterstoomtram, Holland. The equipment provided on these cars is a petrol engine direct-coupled to an electric generator which is electrically connected directly by cables to standard traction motors working through single reduction gear on to the car axles. Speed regulation is obtained by adjusting the speed of the engine and the field current of the generator, and no series resistances are therefore used. The maximum horse-power of the engine which is used on these cars is 90, and it is unwise, in my opinion, to increase the size of engine much beyond this figure on account of the increased fuel cost of larger engines. On pages 117 and 119 of the paper a total engine horse-power of 200 is suggested divided into 2 units of 100 H.P. each, this outfit working a 3-coach train at 25 miles an hour. Examining the total charges per train-mile, using the third-rail direct-current and oil-electric system as given on page 118, it will be seen that the oil-electric system has some advantage, though this is not a very marked one (15·3d. as against 18·8d.), and this confirms the idea that the oil-electric system is not particularly suitable for working standard heavy trains when the increased engine horse-power necessary is considered. The system has, however, been found entirely applicable to railways such as the Arad Csanad Railway mentioned above, where specially light trains running at moderate speeds can be employed. The 90-H.P. engine outfit mentioned is able to haul the motor-car and two light trailers loaded with a total of 150 people at a speed of 30 miles per hour on the level with a total train weight, including passengers, of 52 tons. The cost of running such a train, including fuel, lubrication, stores, wages of driver Mr. Dutton.

Mr. Dutton. and conductor (two men required per train), repairs and cleaning, lighting and heating, comes to less than 5½d. per mile. As the Arad Csanad Railway has had these cars in operation since 1906, this figure may be accepted without any misgiving. In order to make the above figure of cost comparable with the 15·3d. on page 118 of the paper I have taken an outside capital cost for the 3-car train of £4,500; reckoning 15 per cent. of this for interest and depreciation, and assuming that the train runs 100 miles per day, the total cost comes to rather less than 10d. per train-mile, which, I think, may be called an extremely satisfactory figure. With regard to the capital cost of the two systems, the third-rail direct-current and the oil-electric, I had occasion some little time ago to go, in a preliminary way, into the cost of the alternative systems for the equipment of a line 78 miles long which would have required 12 three-car trains to work the service outlined. The capital cost of the equipment on the third-rail basis, including power station, sub-stations, feeders, track, and rolling stock, was more than double the cost of the oil-electric system including track and rolling stock only.

Quite recently a petrol-electric car, supplied by the firm mentioned above, has been put into operation on the Great Central Railway, and is now running between Marylebone and South Harrow. This car is about 42 ft. long, and is fitted with the 90-H.P. equipment as previously detailed.* In actual service the speed on the level with one trailer is 40 miles per hour, and the running expenses are considerably less than the figure given as the cost of operation on the Arad Csanad Railway (5½d.).

Mr. Rankin. Mr. R. RANKIN (*communicated*): The authors' arguments on behalf of the battery system are put forward in an attractive manner, but I think that any reduction that can be made in dead weight should be made up by live weight, and, unless those concerned are prepared to pay a handsome figure for advertisement, the advertising features of the scheme should be dropped to allow of full advantage being taken of the reduction of battery size made possible by the authors' system. The provision of an apparatus by the use of which only half the power used by the wheel-motor undergoes transformation is a distinct advantage. The method of obtaining the result adopted by the authors has the advantage over that used in some systems in which the load is connected between the motor and the generator, that only one machine is required. I think the unsatisfactory working of recent battery locomotives ought not to be laid on the batteries too much; it does not seem to be commonly recognised that a battery can possibly be injured. Batteries made by leading firms are now very reliable indeed, and I think the weakest link in the chain is not the battery but the lack of efficient means for protecting it from unfair treatment. It is to be hoped that the system described in the paper will accomplish what is necessary in this direction, but, for this class of work, the attention of

* Fuller particulars given in the *Railway Gazette*, vol. 16, p. 383, 1912.

users should, in any case, be drawn to the fact that the most rugged and strongest type of plate is the one required. If this is secured the buffer conditions of working should keep the battery in good order, as is exemplified in the case of buffer batteries working under severe conditions in central stations. Attention may be drawn to the fact that there are other fields for the employment of batteries for the propulsion of vehicles; for example, on fire engines and in mining work. In the latter the development of a suitable battery tractor to replace pit ponies would be attended by considerable success. Of course the conditions are more severe here than in the case of ordinary road work, but this field ought not to be closed pending the evolution of the weightless battery which is coming with the hysteresisless iron, and I think that if the problem were vigorously attacked by engineers a good measure of success would result. The sections of the paper dealing with the petrol- and oil-electric vehicles are of interest as describing another application of the accumulator as a load-equalising agent, and, in the latter case, it is pointed out that the disadvantage of any additional battery weight involved is minimised by its being made use of in the process of regeneration. With reference to Fig. 3, I should like to ask why the motor current is shown initially higher than the battery current. Mr. Rankin.

Mr. L. A. LEGROS (*communicated*): In their interesting paper I find several points on which the authors appear to have a misconception of the difficulties prevailing in heavy petrol-driven vehicles in actual practice. Chief amongst these is the impression that the petrol engine is unable to give a nearly uniform torque over a wide range of speed, and that any reduction in the speed of revolution involves loss of compression, inefficient action of the carburettor, and other difficulties. The relation between torque and revolutions for a petrol engine of somewhat similar dimensions to those usual on heavy petrol-driven vehicles is shown in Fig. B. This engine gave a maximum of 38·7 B.H.P., under test on the electrical brake, and when subsequently fitted to a car gave 50·3 ton-miles per gallon of petrol during an independent test made over a distance of some 120 miles. Again, the authors consider the transmission gear as the most expensive item in the upkeep of the vehicle, and doubtless this impression is correct if it be derived from early types of vehicles, many of which are still running; but the introduction within the last three years of the worm-drive has brought about a very great reduction in the upkeep of the back axle and all that portion of the transmission gear between the gear-box and the road-wheels. Their remarks are also very true in respect to the gear-box when they refer to the earlier types of gear-boxes, but here again the improvement effected by introducing chains within the gear-box has led to large reductions in the maintenance of this portion of the vehicle. The fact that braking is often very uneven and that this must keep the maintenence of body, chassis, wheels, and tyres, at a high figure is mentioned, and it is suggested that the use of the electric motor as a brake would overcome many of these difficulties. Braking Mr. Legros.

Mr. Legros. is, however, more a question of the exigencies of traffic than of the method employed to effect the negative acceleration required, and usually it is automatically limited by the magnitude of the coefficient of friction between the tyre and the road, particularly when the latter is greasy, and braking is consequently dependent on the skill of the driver. In some forms of electric brakes the locking of the wheels automatically releases the brake, with the result that the maximum braking effect can be obtained, but it is not clear that the systems discussed by the authors have this advantage. The authors also adduce as inherent advantages of traction by batteries for city traffic the absence of shock and vibration which greatly reduces the wear and

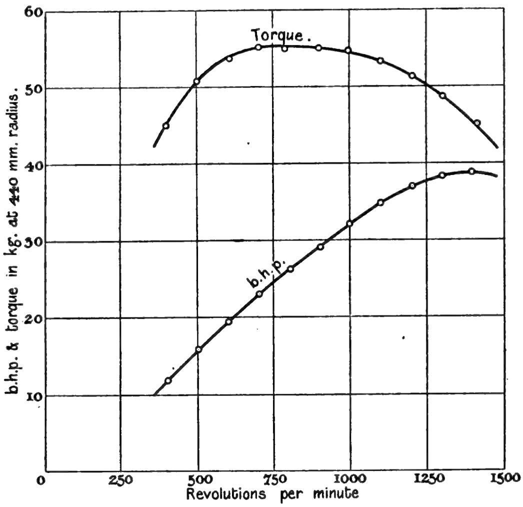

FIG. B.

tear; but as the chassis weights are substantially the same in both cases and the causes of shock and vibration are mainly connected with the road surface and its inequalities, and not with the small periodic vibrations due to the propelling mechanism, it is not clear how the adoption of batteries can reduce these causes of depreciation of the chassis as a whole. The difficulty of the circulating water freezing in severe weather is one which has been encountered also with accumulators, which in cold countries, such as Russia, are occasionally known to freeze. Moreover, in the ordinary touring car it is found frequently that the accumulators used for the ignition require quite a disproportionate amount of attention to keep them in efficient condition. In fact, the use of the magneto, and the displacement of the accumulator by it, has become the rule in most modern forms of petrol-vehicle construction. In the petrol-electric system described in

Section II. of the paper, the authors propose that the engine power be small in order to keep the motor running at constant speed and thereby eliminate water, radiator, pump, and pipes and effect a considerable saving in engine weight. Here I must differ from the authors for the following reason: it has been found generally that the difficulties of cooling the motor increase with the external temperature and with the load at which the engine is run. Thus an engine may run cool with a certain radiator system provided that it is working on a fluctuating load, but on a hot day, or when climbing a long gradient at full load, the system may prove quite inadequate. The very conditions which the authors propose for the small petrol engine are those which are the most unfavourable for efficient cooling by means of air, and the simplicity claimed in this respect would, according to my experience, be found to be very dearly bought at the expense of loss of torque and loss of efficiency due to overheating of the motor, particularly in warm weather. Mr. Legros.

Messrs. J. C. MACFARLANE and H. BURGE (*communicated reply*): In reply to Mr. Roger T. Smith, referring to the question of weight of early petrol-electric systems, we would say that the weight has been excessive, due to the uneconomical methods of working, and to the margin that had to be allowed in the electrical machines to prevent burning out. For example, the range in the relative speed between the motor and dynamo had in most cases to be restricted, with the result that the speed of the vehicle was often partly controlled by varying the speed of the engine. The petrol engine, which only gives its maximum power when running at full speed, had under the above circumstances to be very large in order to give the necessary power during acceleration and when hill climbing. In some cases, however, by the use of resistances between the dynamo and motor, it has been permissible to use a constant-speed engine, but, again, the latter has to be large enough to give the surplus power wasted in the resistance. With reference to energy consumption of heavy electric vehicles in city traffic, very exhaustive tests have recently been made in London with a 6-ton omnibus working on our system, and equipped with a watt-hour meter. The energy absorbed on an out-and-return journey, with frequent stops as under service conditions, was 112 watt-hours per ton-mile, with an average speed of 9 miles per hour. Under similar conditions, Mr. Roger Smith obtained 146 watt-hours per ton-mile on a lorry fitted with partial regenerative control, and at an average speed of only 6 miles per hour. It is evident, therefore, that the control by rotary transformer effects a considerable saving, besides limiting the current that can be taken from the battery. In the case of the petrol-electric rail car with buffer battery, Mr. Roger Smith criticised the power distribution in Fig. 10 as being liable to modification due to signal stops. We cannot see how this can affect the case, as every time the train stops the battery is charged, both during retardation and rest. Further, it is not presumed that the schedule speed of 25 miles per hour would be fully maintained under Messrs. Macfarlane & Burge.

Messrs. Macfarlane & Burge.

these conditions. With regard to the comparative weights of electric equipment, the 24 tons given for the third-rail system includes the electrical apparatus required to work the Westinghouse brakes, and the resistances and contactors for starting and for speed regulation. In the oil-electric system with battery, nothing is included for these items; in fact, we had not allowed anything for power brakes. The rate of acceleration being so chosen as to make the horse-power a minimum, it should be possible to design machines to come within the 12 tons specified. It must be admitted, however, that in the regenerative system the total heating would be greater than has been hitherto experienced with the ordinary traction motor, but assuming that the weight of the machines had to be increased 50 per cent. on this account, the total weight of the train would only be increased by 5 per cent. Referring to Fig. 9, we are not sure that we made our meaning clear. For a regenerative system, given a schedule speed including stops, the average horse-power and speed required from start to stop is definitely settled. What appears to us as more important is to know the least horse-power required during acceleration (in order that the distance may be covered in the specified time), so as to determine the size of the battery and engine. The latter should be made large enough to give the average horse-power mentioned above, plus what is required to make up for the average power lost in the equipment. We get the least horse-power during acceleration by arranging the maximum speed to be 1·5 times the average speed, as shown on page 116.

With regard to Mr. Stevens's remarks, the energy returned to the battery in the electric bus when operating in traffic has already been referred to. As regards the power required to drive this vehicle, recent tests in London showed that the road resistance varied from 25 to 28 lbs. per ton. Referring to the 9-H.P. air-cooled engine, the weight 196 lbs. complete is made up as follows: Engine, silencer, air-cooling system, and light flywheel (the electric machine providing part of the flywheel effect), 110 lbs.; petrol and lubricating tanks when full, 86 lbs.

Mr. Seabrook gave some interesting figures showing that a very large number of electrical vehicles are in operation in America, and we agree with him that the matter deserves more consideration by our electric supply authorities than hitherto, seeing that even at ½d. a unit a considerable profit might be realised.

Mr. Hedley Thomson asked a question as to weights of the several parts of the electrical equipment. With the exception of the controlling and starting gear, which weighs about 40 lbs., the weight is equally divided between the rotary transformer and the motor. Mr. Thomson criticised the maintenance figures, but it should be pointed out that in the petrol case the chassis maintenance includes the entire upkeep of the engine with all its accessories, such as water-cooling and ignition systems, also the change-gear box and the clutch. Now, in the electric case we only have the electric machines, the

maintenance of which would be insignificant in comparison. Again, for "washing and preparing for running," we may mention that Messrs. Frost-Smith and Stevens in their paper read before the Society of Road Traction Engineers,* give day and night running charges as 1·015d., and we know that our item 0·17d. for the electric bus covers the cost of washing, there being no lubricants, petrol, or water to replenish. Messrs. Macfarlane & Burge.

In reply to Mr. Wimperis, who calculated that the controlling torque would not hold the omnibus on a steeper gradient than 1 in 50, he has overlooked the fact that when standing on the level the motor, in order to move the bus backwards, has to overcome the gear friction in addition to the tractive effort required due to road friction, whereas when going downhill the bus has again to overcome the gear friction in addition to that of the road, and the result is that the bus will actually remain stationary on any gradient up to 1 in 28, which represents the steepest part of Ludgate Hill. Mr. Wimperis is correct in suggesting that the acceleration is proportional to the amount which the pedal is forced down. We have not made any measurement of the acceleration, which probably varies from moment to moment, but it may be of interest to mention that the acceleration at starting exceeds that of any omnibus, whether steam or petrol, running in London. With regard to the tractive effort required, we find this to be 25 to 28 lbs. per ton in London with roller bearings. Referring to the 9-H.P. engine proposed, the point we wished to emphasise was that, given the opportunity of running the engine at constant speed and power, the battery providing for overloads, the engine could be sufficiently small to be air-cooled. The fuel consumption of 1 gallon for 14 miles was based on the assumption of a 9-H.P. engine working continuously at full load. With regard to the rate of retardation shown in Fig. 9, it would be easy to arrange for this to be very much greater in practice by bringing the controller more rapidly to the "off position."

Referring to Mr. Wimperis' concluding remarks, in saying that "it does not matter whether the rate of acceleration is constant or not so far as the average power required to accelerate the train in a certain time is concerned," what we mean is that this being the case we can, to simplify matters, assume uniform acceleration, the average power depending on the rate of acceleration adopted. To accomplish the journey in the required time, we may adopt a high acceleration, getting up to speed in a short time, and a low maximum speed, or we may have low acceleration and high maximum speed, but the calculation on page 23 shows that, to reduce the average power during the starting period to a minimum, the acceleration period should be such that the maximum speed is 1·5 times the average speed between stations.

In reply to Mr. W. E. Robson, we may say that we do not agree with him that during acceleration there should be a graduated supply of power and a constant torque. This would mean a very small current

* *Electrical Engineering*, vol. 3, p. 475, 1908.

Messrs. Macfarlane & Burge.

from the battery at the instant of starting, and a very large current at the end of the acceleration period. Now, when drawing power from any source it has always been the engineer's aim to keep the maximum peak load down as near as possible to the average load, *i.e.*, to have a high load factor. When the power is supplied from a battery, this is imperative, owing to the rapid falling-off of capacity with high discharge rates. A certain average power is required to accelerate the vehicle in a given time, and it is desirable that the power be kept up to this value all the time, and full speed will then be reached without exceeding the average power to any extent. Mr. Robson is correct in assuming the range of 50 miles to apply only to a straight run, and for the reasons he stated the mileage is reduced somewhat when frequent stops are made. With regard to the greater variation of voltage possible with a motor booster, we may say that a greater range than that proposed would be undesirable and would lower the efficiency and increase the size of the machines. The characteristics of the rotary transformer in combination with the field windings of the motor C cause that machine to operate in a very similar manner to a series motor and at the same time allows of regeneration without changing the connections. From an inspection of curves 3 and 4, Fig. 3, it will be seen that the torque-speed and current-speed curves are similar to a series motor supplied with constant voltage. In a series motor, the full strength is reduced as the current falls off, so also in the case of the motor C, any falling off in current is immediately followed by a weakening of the field automatically. Referring to the statement that the bus was capable of accelerating in 1½ to 2 lengths, it must be admitted that the bus was not loaded and that there may be some uncertainty as to when full speed is reached due to the rise in speed being very gradual at the end of the acceleration period. We may say that the weight on the back axle is considerably more than on the front axle. In regard to all-electric *versus* petrol-electric systems for cities, the choice of the former, though slightly more costly, is obvious for reasons repeatedly set forth in the paper.

Replying to Mr. Taylor, we may repeat that the tractive effort required in the streets of London rarely exceeds 28 lbs. per ton, and is as low as 25 lbs. on asphalt.

Mr. Burnand's suggestion of carrying a battery on a train to absorb the regeneration while the train is pulling up, the acceleration power being taken from conductor rails, still means a large battery to take the heavy charging current which nearly reaches the same value as the accelerating current.

Mr. W. R. Cooper's questions have been practically answered already in our replies to previous speakers.

The information given by Mr. H. N. Dutton with regard to the costs of oil-electric trains and their comparison with the third-rail system is very interesting, and points to the wider adoption of the former in the near future.

In reply to Mr. R. Rankin, the motor current is initially higher than

the battery current due to the transformation ratio of battery voltage to motor voltage obtained by means of the rotary transformer. Messrs. Macfarlane & Burge.

In reply to Mr. L. A. Legros, the electric braking system proposed is undoubtedly one in which the locking of the wheels reduces the braking effect, tending to prevent skidding.

Proceedings of the Five Hundred and Thirty-fifth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, 7th March, 1912—Mr. S. Z. DE FERRANTI, D.Sc., President, in the chair.

The minutes of the Ordinary General Meeting, held on 22nd February, 1912, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members—

James S. Brown. | Ernest A. Laidlaw.

From the class of Associates to that of Associate Members—

George William Somerville.

From the class of Students to that of Associate Members.

Sydney A. Joyce.
Walter C. Lambourn.
D. S. Maclachlan.
Kingsley Douglas McMillan.
Henry C. R. Martin.
Vernon Wm. Newman.
James Parkinson.
William Robert Poole.

Messrs. J. R. Dick and A. Howell were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Members.

Thomas Britten. | Eustace Stanley Dashwood.
Alfred O. Kolkhorst.

ELECTIONS—*continued.*

As Associate Members.

Edmund Archibald Baëza.
Frederic Dean Balshaw.
Herbert Thomas Bates.
Frank Coates.
George Frederick Craven.
Ernest James Dutch.
Alfred Henry Dyer.
Harold Fildes.
Ernest Henry Glennie.
Herbert M. Harding.
Thomas Crespin Harrison.
William Trewyn Hawken.
John Alfred Hunn.
William Ferrier Keith.
William Hay M. Kelman.
Alfred Edward McCloskey.
Albert Edward McColl.
William Richard Macdonald.
Charles Henry McKeown.
Thomas Alfred G. Margary.
Michael Mulligan.
Walter Joseph Newton.
Charles Halsted Noyce.
Gerald Hamlin Randell.
Stanley Fred Richards.
John Roberts.
Thomas Arthur Smith.
Charles Douglas Stanley.
Herbert William Swann.
Howard Church Symmes.
Harold Stanley Taylor.
William Ewart Tremain.
Sydney Weatherburn Watson-Weatherburn.

As Associates.

Ernest W. Beech.
John William Breeze.
Alfred Lord Lintott.
Francis Milward Smith.

As Students.

Frederick George Beaton.
John Wilson Beck.
Edward John Billington.
Alexander Brook Black.
David Blairmann.
Harold Boardman.
Charles Augustus Bold.
Clement Wildsmith Bostock.
Thomas Everard Bridge.
Arnold Craven.
James Gaunt Craven.
Noshirvan Jehanghir Cursetjee.
I. Gustave D. de Grandpré.
Alfred Dixon.
Thomas Lyall Dowey.
Thomas Dowse.
Peshoton Sorabji Dubash.
Ferdinand Farrant Duckworth.
William Duckworth.
David Dunham.
Noel D. Edingborough.
Lionel Gladstone Edwards.
Alfred Ernest Elliott.
Robert Evans.
D'Arcy George Fisher.
Francis William Fisher.
James Mason Fishley.
George Ormonde F. W. Fitz-water.
Leslie Gabriel Floyd.
Walter Gibson.
William Albert Gillott.
George Harle.
Ranald John Harvey.
Arthur Leslie Howe.
Harry Langford James.
David Jones.
Gerald Leslie Kindred.
Henry Boswell Lee.
John William Leech
Edward Levi.
Angus McPherson.
William Charles Mallett.
Cecil William W. Manlove.
Geoffrey Edward Martin.
Robert Ruthven Martindale.

ELECTIONS—*continued.*

As Students.

Henry Alfred Miles.
Vincent Henry G. Parker.
Richard Peart.
Albert Edward Phillips.
Kenneth Mallorie Priestman.
Arthur Rawlin.
John Renton.
Hubert Robertson.
Douglas Harry Robinson.
Robert Sellars.
Nelson Sizer.
Alan Leonard Smith.
George Smith.
Vincent Smith.
Cecil Arthur Stephens.
Leslie Rigg Story.
Michael Joseph Tormey.
Maurice Wadeson.
Alexander Ward.
John Ward.
William Kirby Weston.
Philip John Wheeler.
Charles Frank H. White.
John Gordon W. Winn.
Philip Wrigley.
James Young.

Donations to the *Building Fund* were announced as having been received since the last meeting from R. H. Burnham, H. C. Channon, A. D. Constable, R. A. Dawbarn, S. Z. de Ferranti, D.Sc., Dr. C. V. Drysdale, A. H. Findlay, S. E. Glendenning, R. Hardy, Professor A. Hay, J. F. Henderson, J. S. Highfield, H. Hirst, Vice-Admiral Sir H. B. Jackson, K.C.B., F.R S., H. W. Kolle, G. C. Lloyd, W. M. Mordey, S. R. Roget, J. H. Rosenthal, J. F. C. Snell, M. Solomon, A. Stroh, Sir Joseph Swann, F.R.S., T. C. T. Walrond, A. Wright, and H. W. Young; and to the *Benevolent Fund* from G. F. Allom, L. B. Atkinson, M. S. Chambers, R. A. Chattock, W. C. Clinton, W. W. Cook, V. K. Cornish, B. Davies, A. Denny, J. Devonshire, H. C. Donovan, B. M. Drake, Dr. C. V. Drysdale, K. Edgcumbe, Dr. R. T. Glazebrook, C.B., F.R.S., F. E. Gripper, C. C. Hawkins, K. Hedges, D. Henriques, J. S. Highfield, S. H. Holden, H. A. Irvine, E. S. Jacob, Dr. G. Kapp, H. W. Kolle, A. E. Levin, Sir H. C. Mance, C.I.E., E. Manville, W. Mead, C. H. Merz, L. B. Miller, W. M. Mordey, Major W. A. J. O'Meara, C.M.G., Hon. Sir C. A. Parsons, K.C.B., F.R.S., W. H. Patchell, W. O. Pepper, A. H. Preece, L. Preece, Sir Wm. Preece, K.C.B., F.R.S., T. Rich, R. Robertson, S. R. Roget, W. H. Scott, J. S. Sellon, A. Siemens, J. B. Smith, J. F. C. Snell, A. Stroh, A. J. Stubbs, A. P. Trotter, T. C. T. Walrond, H. W. L. Ward, and J. G. Wilson, to whom the thanks of the meeting were duly accorded.

A paper by W. W. Lackie, Member, entitled "Tariffs for Electrical Energy, with particular Reference to Domestic Tariffs," was read and discussed (see page 147).

TARIFFS FOR ELECTRICAL ENERGY, WITH PARTICULAR REFERENCE TO DOMESTIC TARIFFS.

By W. W. LACKIE, Member.

(*Paper received* 19*th January; read before* THE INSTITUTION 7*th March, before the* SCOTTISH LOCAL SECTION 13*th February, before the* MANCHESTER LOCAL SECTION 27*th February, and before the* NEWCASTLE LOCAL SECTION 22*nd April*, 1912.)

Many papers have been written on systems of charging for electrical energy and on tariffs for electricity supply. Owing to the ever-changing aspects of the subject, and to the growth of exact knowledge with regard to the various factors concerned, the methods of charging still invite fresh consideration and treatment. No apology is needed, therefore, in bringing the subject of tariffs before this Institution once more.

No paper on tariffs for electrical supplies should be introduced without mentioning the pioneer work of Mr. Arthur Wright, and of his invention, the maximum demand indicator. It was Dr. Hopkinson who gave us what at first sight does not appear to be an axiom, viz., that the cost of a supply of electrical energy does *not* depend so much on the number of Board of Trade units taken as on the maximum rate at which the units are taken.

Mr. Edward Cowan made an interesting contribution on this subject two years ago to the Royal Society.

The accounts of electrical undertakings are frequently adversely criticised by non-technical financial journals which do not acknowledge the principles underlying the maximum demand system of charging. For this reason I here put forward the accounts of two consumers, A and B, under three differing sets of conditions, viz. :—

1. With an equal number of units used by each.
2. With an equal annual bill paid by each.
3. With an equal maximum demand made by each.

A taking a supply for 200 hours per annum, and B taking a supply for 2,000 hours per annum, the rate of charge being 730 hours' use of the maximum demand quantity at 3½d. per unit, and all energy in excess of this at ¾d. per unit.

It is clear from the figures here given that to charge A and B the same average rate would be unfair. It is difficult to persuade the consumer who takes energy for less than 1 hour per day and who pays 3½d. per unit, that he is not being over-charged. He knows that the

	Units.	Plant Required.	Capital Cost.	Amount of Account.	Average Price.	Interest, Sinking Fund, and Depreciation, at 8 per Cent.
			I. Equal Units.			
		Horse-power	£	£ s. d.	d.	£ s. d
A	1,460	10	400	21 5 10	3½	32 0 0
B	1,460	1	40	10 16 8	1·78	3 4 0
				£ s. d.		
	Minimum loss on A ...			10 14 2		
	Gain on B			7 10 0		
			II. Equal Bills.			
A	1,460	10	400	21 5 10	3½	32 0 0
B	2,900	2	80	21 5 10	2·01	6 8 0
				£ s. d.		
	Loss on A			10 14 2		
	Gain on B			14 17 10		
			III. Equal Maximum Demands.			
A	1,500	10	400	21 17 6	3½	32 0 0
B	15,000	10	400	109 12 3	1·75	32 0 0
				£ s. d.		
	Loss on A			10 2 6		
	Gain on B			77 12 3		

average rate received by the supply authority is, say, 1½d. per unit, and he imagines that he is taxed to contribute to this result. This, of course, is a fallacy. Were it not for the consumer who gets his energy at 1·7d. per unit, the charge would need to be increased from 3½d. to a much higher figure.

The cost per unit of supplying electrical energy depends—

1. Upon the maximum rate at which the supply is demanded;
2. Upon the number of Board of Trade units taken;
3. Upon the time of day at which the demand is made;
4. Upon whether the supply is taken evenly and regularly over the 365 days in the year, or taken in the winter months only, and then for a few hours a day (at times of darkness or during fog); and—
5. On the number of consumers being supplied.

It is admitted that in some cities and boroughs it is unnecessary to adopt the maximum demand system in its original form, although the basis of the rates of charging is an adaptation of the system. In such cities and boroughs there are no huge tenements of offices with excellent daylight, and on the whole the majority of the consumers in such towns have similar load factors within a variation of 5 to 6 per cent. In such circumstances the giving of discounts for larger quantities might even be justified irrespective of load factors.

The city about which I know most, however, has many huge tenement blocks of offices with load factors of 5 or 6 per cent., but there are also other offices having large basements with a load factor of over 20 per cent. It is a misfortune that there is a class of consumer who requires a supply equal to half an hour per day only, but after all such consumers cannot help the circumstances which limit their use of energy, and I do not argue that they should be charged abnormal rates. They have at least contributed their quota in popularising electric lighting when it was less generally used than it is now, and, if they were to use the energy for a longer time, it would be wastefulness on their part. Some of these consumers do not take their supply at a time when the maximum demand on the generating station is being made. The probability is that the only extra capital expenditure entailed in supplying these consumers who take a supply for less than 1 hour per day is expenditure on plant. It could be reasoned that the mains laid would not have been appreciably diminished in extent if office lighting had not been demanded; and the mains represent half the capital expenditure on any electricity undertaking. It might further be contended that the depreciation on plant that is used for only 1 hour per day should be very much less than the depreciation on plant that is used for 10 hours per day, and consequently the consumer who uses the supply for only 200 hours per annum should not be charged the same rate of depreciation as those who use it for a longer time. This might mean that the amount of depreciation charged against the other consumers should be increased, but it might also be an argument for decreasing the total amount of depreciation, which is now charged on a scale based on the assumption that the whole of the plant is used for the maximum number of hours. The fact is that electric lighting undertakings have suffered in the past not so much from depreciation of plant as from plant having become

antiquated. Interest and sinking fund must be charged on the basis of the maximum demand.

If, therefore, those 1-hour consumers are debited with only half the capital expenditure per kilowatt (*i.e.*, on plant only), and have a reduced rate of depreciation allocated against them, they will not present such a deplorable balance-sheet as that shown in the table annexed.

It is also agreed that if the consumers who take their supply for 1 hour and under were not connected, some of the standing charges, at present allocated against them, would have to be made up by the other consumers.

I think that this table shows the necessity for the maximum demand system of charging in large cities, and it further shows where a reduction should be granted with any surplus. It has appeared to me that in fixing a price for electrical energy there are other things to be kept in view besides the maximum demand principle. Mr. Seabrook, in his recent paper on tariffs, gave one of these other things as "Expediency." I agree with him. Another factor to be considered is the cost per annum or per unit at which any consumer can get an equivalent supply by installing his own plant. Although a consumer agrees to take his supply at a time other than when the bulk of the consumers make their demands, there is no need for a supply authority to sell electrical energy at the bare cost of coal and oil, because no consumer can generate energy for himself at the bare cost of coal and oil. Any profit made by supplying such consumers goes to the credit of supplies to all the consumers exactly in the same degree as any loss incurred in supplying certain consumers must be borne by all the remaining consumers. It follows that there is no necessity for supplying electrical energy for lighting at less than 3d. per unit to the average consumer in a town or district where the price of gas is 2s. per 1,000 cub. ft. or more, even though such lighting is used only between 7 p.m. and 5 a.m.

Few persons who have looked closely into the subject will say that the maximum demand system of charging is unsound. Several prominent engineers have stated that they do not think that the system is perfect because it does not take into account the actual time of day when the maximum demand is made. This is not accurate. It is true that the maximum demand system does not indicate or recognise the actual hour at which the maximum demand of any particular consumer occurs, but it does recognise the extent to which the aggregate maximum demands of the consumers do *not* occur simultaneously. In other words, it does recognise distinctly whether or not any group of consumers take their supply during those hours when the maximum demand is being made by the mass of the consumers. The amount of plant to be installed to supply any given total number of consumers connected is decreased in proportion to the extent to which the maximum demands of these consumers do not occur at the same time; and this means that the standing charges, represented by interest and depreciation, are reduced; so that the maximum demand system takes

cognisance of the time when the maximum demands are made by reducing the charges to all the consumers. The system is equitable and fair because of this fact. Any flat rate, or even an approach to a flat rate, must have as its basis the maximum demand system of charging if it is to be equitable. For instance, against a rate of 3½d. per unit for lighting, a charge of 1½d. per unit for power is fair, because the power supply will be used for at least three times as many hours per day or per annum as the lighting supply is used.

In the table attached an analysis is given of over 20,000 consumers' accounts. In this an extreme view has been taken, *i.e.*, all charges except coal and carting (for the removal of ashes) have been divided among the consumers in proportion to their maximum demand, and coal and carting have been taken as just under one-fifth of a penny per unit. This was the average cost for 1911 in Glasgow. It is not difficult to show that consumers taking a supply for under 2 hours per day cost considerably more for coal than the average price per unit. Conversely those consumers who use their supply for 5 hours and over could reasonably be charged less than the average price for coal and for carting.

This analysis shows that it is necessary to get a revenue of £9 per kilowatt of maximum demand, including coal and carting. This is made up of £7 17s. per kilowatt of standing charges, and 0·191d. per unit for coal and carting, the average cost for coal and for carting being £1 3s. per kilowatt. A figure to be noted is that the plant required is stated at 27,475 k.w., whereas the maximum load on the station was 23,524 k.w., or 16 per cent. less kilowatts than the summation of the individual maximum demands of the consumers. The difference between these two figures is of course accounted for by the diversity factor amongst the maximum demands of the consumers. For instance, churches are practically never open during the time of peak load, and theatres, halls, and schools are seldom lit between the hours of 3.30 and 6 p.m. It is also found that the maximum demand in residential districts is an hour later than that in the industrial or business districts. The opposite extreme to that given in the table annexed is to make the running cost ¾d. per unit, and this would enable us to reduce the standing charges to £4 10s. per kilowatt. If it were possible to make those consumers who use their supply for less than 1½ hours per day pay up this £7 17s., or even £4 10s. per kilowatt, it would allow, with the present capital charges, a reduction of almost £1 per kilowatt per annum. If the running cost is made ¾d. instead of 0·191, the 1-hour consumers and under still show a loss of £13,200, and the consumers taking a supply for over 1 but under 2 hours will show a profit of just under £3,000. The domestic consumers show a profit of £6,000, no matter which running charge is adopted. This sum will pay standing charges on a further 2,000 k.w. of maximum demand made in domestic premises if the energy is charged at 1d. per unit. This analysis is not to be taken as an absolutely accurate balance-sheet. The maximum demands given in the column headed "Amount

of Plant Required" have in many cases been estimated. In all business premises maximum demand indicators are erected except in those premises where the supply will not be used for anything like 2 hours per day. In theatres and large works recording ammeters are used to get a fair maximum demand, but in domestic premises the maximum demand quantity has been arrived at by a maximum demand indicator or recording ammeter connected in the feeder or main supplying a hundred or more tenement consumers at one time. The maximum demand against domestic consumers given in the analysis therefore already allows for a diversity factor. It must also be borne in mind that the diversity factor in a power supply is very much greater than in a lighting supply, and consequently the amount of plant required for power demand stated is excessive. The analysis shows that any of the following rates would give the same financial result:—

Charge per Kilowatt per Annum.	Pence per Unit.
£ s. d.	
7 17 0	0·191
7 8 0	0·250
6 0 0	0·500
4 10 0	0·750
3 0 0	1·000

Increasing the running charges from 0·19 to 1·0d. per unit is out of the question as our total generation, distribution and management charges were under 0·5d. per unit. It is of interest to note that the actual cost of the additional units shown as an increase over each previous year during the past ten years is just under 1d. per unit.

As I believe the supply of electrical energy to domestic consumers is of vital importance in all large cities which are at present faced with the smoke problem, and are striving to bring about a purer atmosphere, I should like to draw attention to what has been done in Glasgow to encourage the use of electricity by domestic consumers for purposes other than lighting. A private supply company who had resolved to encourage the further use of electricity or who were anxious to counteract a diminution in their lighting load for domestic consumers (caused, for instance, by the introduction of the metal filament lamp) might easily advise their consumers that any units taken over the previous year's consumption would be charged at a lower rate per unit. I question very much if, in such circumstances, a municipal undertaking, or a private concern would object if the consumer added to his consumption by increasing the number or candle-power of the lamps

already installed, although the object of offering the lower rate for extra units might have been to encourage the use of energy for such purposes as cooking, heating, operating vacuum-cleaners, knife-cleaners, etc.

A private company can and does do many things that a municipal concern may not do. It was therefore necessary to devise a scheme which should have the same effect as that just described, but which should have an established relation to our general system of charging.

The rates of charge for lighting purposes in Glasgow up till 1901 for business premises and for domestic consumers were 6d. per unit for the first 365 hours' use of the maximum demand, and 1d. per unit for all further quantities. At that date an analysis of the accounts of all our consumers was made in order to find whether a flat rate of charge could be fixed for different kinds of business premises, such as tea-rooms, public-houses, shops, banks, and clubs. This analysis showed that the only class which used the supply for the same length of time throughout the year were the domestic consumers, it being found that they used their supply for fully 2 hours per day or 730 hours per annum. It therefore became a simple matter to convert the charge of 6d. per unit for the first 365 hours' use, and 1d. thereafter, into a flat rate of 3½d. per unit. This was done. The domestic flat rate has since been lowered to 3d. per unit for lighting. Where a flat rate has been fixed on the basis of the maximum demand, it does not matter if a consumer increases the candle-power of the lamps already installed, as the load factor will remain the same so long as the consumer continues to use the installation for the same number of hours. Inasmuch as the flat rate is based on a given number of hours' use of the maximum demand per annum, and not on the extent of the maximum demand, the installation of more or of larger lamps adds to the total consumption in proportion to the increase in the total maximum demand thereby effected without interfering with the flat rate.

The return of the accounts now given on the annexed table shows that the domestic consumers use their supply for nearly 3 hours per day. This can be accounted for by the fact that since 1901 a large number of smaller houses and tenement flats have been connected to our mains, and there is no doubt that such houses have a better load factor than large private residences, for the reason probably that, alike on account of their situation and the extent of their window space, they are unable to take full advantage of the hours of daylight. It is probable also that the average number of hours per day has been increased as the smaller domestic consumer has realised that electric lighting is not prohibitive with regard to cost, and therefore that there is no need for any undue economy in the use of it. Moreover the smaller householders do not vacate their city residences for such lengthened periods throughout the year. It should also be noted that the maximum demand of the domestic consumers given in the analysis already allows for any diversity factor.

With the problem of black smoke and atmospheric pollution in one's mind, it was needful to devise a scheme which would enable

the domestic consumer to get a supply of electricity for heating, cooking, etc., at a lower rate, without being put to the expense of separate wiring, with a separate meter, etc. An analysis of between 500 and 600 purely domestic lighting accounts was instituted, and the average number of units noted for one, two, three, four, five and six rooms and kitchen-houses, and large private residences. These were also classified according to district. It was demonstrated that four rooms and kitchen-houses, of the same size as regards cubical contents, were, on the whole, consistent in their consumption of electricity for lighting purposes. As there were reasons for believing that many of these consumers would use electric radiators, vacuum-cleaners, electric irons, etc., if it could be shown that this could be done without initial expense or relatively large outlay, it seemed desirable to meet such cases by a method of charging which would give them their heating and power units at a lower rate. Having ascertained that domestic consumers' premises, similarly situated, and of the same size, were practically consistent from month to month, in the nature and the extent of their consumption for lighting, it was a simple matter to devise an adaptation of the maximum demand system which would meet their case. As their average use of the lighting maximum demand was 800 hours per annum and the charge was 3d. per unit, it was suggested that all energy consumed over this quantity should be charged at 1d. per unit. In order to enable the consumers to realise that they were getting their extra units at the lower rate, a proportionate number of lighting units was allocated to each of the two-monthly bills, and whatever number of units might be consumed over this minimum in each two months were to be charged at 1d. per unit. The division of the 800 hours' use of the maximum demand over the six periods into which the year is divided was as follows :—

	Hours' Use of Maximum Demand at 3d.
June–July	40
August–September	60
October–November	200
December–January	300
February–March	160
April–May	40
Total	800

All further units at 1d.

The number of hours given corresponds to the hours of darkness from sundown to 10 p.m. each two months; and it was found that the domestic consumers' accounts also gave approximately this result.

In recommending this system of charging for heating and power in domestic premises, I ventured to prophesy that it would increase the output without adding to the expenditure on branch mains, fuses,

meters, meter readers or administration, and that it would lead to a considerable use of electricity for intermittent heating in spring, summer, and autumn, when fires are generally off and only occasional heating is required, and these are the times of the year when there is a considerable amount of the station plant standing idle, *i.e.*, earning no revenue.

The average account of the domestic consumers is shown to be £2 16s. per annum.

There are at least three charges which can be treated very largely as per consumer and not as per kilowatt, viz. :—

1. The capital cost of the branch, which varies very little with the extent of the individual demand.
2. The capital cost of the meter.
3. The cost of reading the meter, rendering the account, and maintaining the meter.

It was found that it cost 7s. per annum for the maintenance of the meter, and to read it and render an account, and consequently this charge represents 12½ per cent. of the cost of supply to a domestic consumer. If a separate meter were needed for recording the energy used for heating and cooking, this would have meant an additional 7s. per annum.

It should be noted that in formulating this system of charging, the data allow for the domestic consumers being absent from the city for one or two months per annum.

Had the method of applying the maximum demand system of charging been strictly adhered to, at 3½d. and ¾d., and had 730 hours use of the maximum demand been charged first at the higher rate, it would have meant that from June 1st to November or December, domestic consumers would have been charged 3½d. per unit for all the energy used, and then from January 1st to May 31st the price would have dropped to ¾d. per unit. The consumers would therefore have had difficulty in appreciating the fact that during the period from June to December, they were getting their heating units at the 1d. per unit rate; and to that extent, I feel sure, the literal application of the maximum demand system would have acted as a deterrent to the extensive adoption of domestic electrical apparatus, which has taken place since our modified rate for domestic consumers was introduced. The fact that each two-monthly bill shows its own proportion of 1d. units tends to encourage domestic consumers to use radiators, irons, vacuum-cleaners, etc., without hesitation. This is a case where expediency in charging is preferable to rigid adherence to a fixed principle.

This system of charging for additional units at 1d. to domestic consumers has now been in use for one year. Over 500 consumers have installed electrical apparatus of some kind. One hundred of these domestic consumers' accounts, examined at random in different parts of the city, show an increased consumption of 21 per cent. as compared with the corresponding period of the previous year. This

represents 7 per cent. increased revenue. If the domestic rate for lighting had simply been reduced, the probability is that the bills examined would have been less, instead of greater, than the corresponding bills for the previous year.

Four years ago we were making general reductions in our rates. The domestic consumers' lighting rate was then reduced from 3½d. to 3d.; and shops, warehouses, and other business premises had the maximum demand system modified then so that instead of being asked to pay for 365 hours' use of their maximum demand at 6d. as above indicated, they were asked to pay for 730 hours' use of their maximum demand at 3½d. before being charged the ¾d. rate. This gave the consumers who used their supply for under 2 hours a reduction on their rate; but as a matter of actual experience we found that business men knew what they had to pay for lighting their business premises, viz., 6d. per unit, and did not trouble to acquaint themselves with the domestic rate, the result being that they refrained from having electricity in their homes. We have reason to believe, therefore, that when business men saw their business premises account being rendered for 3½d. per unit, it had a beneficial effect on the demand for energy for domestic lighting.

If different persons, in similar houses, have, in a few cases, a different consumption, that is not a sufficient reason for stopping a movement which will simplify the tariff for the general supply. The tariff might make those exceptional cases in which the bills seem unduly low, light up their premises to a larger extent than they otherwise would have done; whereas those whose bills seem higher than the average, can either economise or, alternatively, they may be entitled to have their extra units at a lower rate.

It is now admitted that the domestic chimney is mainly responsible for atmospheric pollution. Municipalities must, therefore, as a branch of their activities in connection with the general movement towards public health, recognise the importance of nursing their electrical undertakings by encouraging the use of electrical energy for all domestic purposes. Sir Arthur Newsholme has shown that the £60,000,000 spent per annum in England and Wales on public health, brings in a return of £3,000,000 in wage-earning capacity conserved, and in expenditure saved in medical attention, nursing, and infirmary charges. This is the doctor working in his new rôle of applying the adage that "prevention is better than cure." I submit that it would be an enlightened policy on the part of the local authorities and of the nation to encourage the use of electrical energy for domestic purposes by educating the public regarding the possibility of electrical apparatus and giving energy at the lowest possible rate. To this end the recently developed policy of taking the surplus revenue from electrical undertakings for the reduction of city rates should be condemned and at once abandoned; and not only so, but electricity supply concerns, both municipal and private, might reasonably ask to be relieved from paying rates, if it could be shown that, to this extent, they were lowering their prices to domestic consumers.

The system of charging, now advocated, leaves it quite open, either to add to or deduct from the number of units chargeable at 3d., if there is any known reason, such as abnormal increase or decrease in the lighting demand. It is not difficult to see from a recording ammeter chart how much energy is demanded for lighting and how much energy is demanded for "other purposes." There is a natural law, by which all consumers require light during the hours of darkness, *i.e.*, from sunset till 11 p.m. Lamps take one-tenth of an ampere for a 16-c.p. lamp and 2 or 3 amperes for a large electrolier, whereas a 4-lamp radiator or an electric oven takes double this amount, and is used at odd times during the day. This method of using a recording ammeter has been adopted in fixing the lighting demand in the larger houses. It has also been used to ascertain the maximum demand in engineering works, where the consumer, having previously generated his own energy, had not the wiring on separate circuits for lighting and for

Date of Period.	1 R and K.		2 R and K.		3 R and K.		4 R and K.		5 R and K.		6 R and K.	
	Units.	s. d.	Units.	s. d.	Units.	s. d.	Units.	s. d.	Units.	s. d.	Units.	s. d.
June–July..	2	0 6	4	1 0	6	1 6	10	2 6	12	3 0	13	3 3
Aug.–Sep...	4	1 0	6	1 6	10	2 6	15	3 9	17	4 3	20	5 0
Oct.–Nov...	13	3 3	18	4 6	30	7 6	50	12 6	57	14 3	65	16 3
Dec.–Jan...	19	4 9	24	6 0	44	11 0	75	18 9	86	21 6	97	24 7
Feb.–March	10	2 6	14	3 6	24	6 0	40	10 0	46	11 6	52	13 0
April–May	2	0 6	4	1 0	6	1 6	10	2 6	12	3 0	13	3 3
	50	12 6	70	17 6	120	30 0	200	50 0	230	57 6	260	65 0

power. It would have been a distinct hardship and would have been an obstacle to such consumers taking the supply from the Corporation, if they had been asked to separate their wiring so as to have distinct circuits for lighting and for power. Even in the winter months it is easy to see, from a recording ammeter chart, what the lighting demand is, and this can be confirmed by comparing the winter chart with the summer chart. The rate of charge or maximum demand quantity has been increased proportionately, to make up for the lighting demand, and all energy is charged at power rates, or a fixed annual sum is charged to cover the difference between lighting and power rates.

To abide rigorously by the Hopkinson method, which means charging, say, £5 per kilowatt plus ¾d. per unit, has disadvantages. It was tried in Glasgow, but consumers objected to it. Their bills were very much the same the whole year through, and we had serious complaints from people who received a bill for electricity either when their house was shut up or when they were not consuming any energy. In the winter months, of course, there was not the same cause for complaint. Dividing the maximum demand units equally over the six

Mr. French. two-monthly periods will have the effect of giving the consumer a very large number of units at the low rate in the winter months and none at all in the spring, summer, or autumn months. The objections now stated to the Hopkinson and other systems, which are arranged on dividing the standing charges equally over the year, do not apply to power consumers' accounts, as their consumption is, as a rule, regular and consistent from month to month.

As already indicated, each two-monthly period is allowed to stand by itself; and if a domestic consumer is absent from his house during the whole of any one two-monthly period, he is not asked to make up the units allocated against that period. On the average, the quantities payable at 3d. per unit for the different sizes of house, varying from one room and kitchen to six rooms and kitchen, are shown in the table on page 157.

Simplicity must be aimed at in every method of charging, and I think that we can claim that our systems in Britain are ahead of those of our American cousins in this respect. The Edison Electric Illuminating Company of Boston publish an 8-page pamphlet giving their schedule of rates.

Discussion.

The President. The PRESIDENT: You now have before you Mr. Lackie's very able paper on this subject. You have also had another paper by Mr. Seabrook on much the same subject. Both these papers are part of a scheme which the Institution is carrying out, a scheme which I believe is of very great importance to the industry generally. We want to use every means in our power to promote the much wider and more general adoption of electricity for domestic purposes. Some time ago it was arranged that we should not only have papers such as you are used to hearing, but that we should occasionally have evenings upon which we might have what may be called informal discussions. It is proposed that these discussions be opened by a short statement on the subject, and to rely at such meetings principally upon the discussion. The very fact of the meeting not being formal will, I believe, greatly help many speakers who would otherwise not care to give their views. The first of those meetings will take place on the 21st of March, when I hope to have the pleasure and privilege of introducing a subject for discussion. That subject is part of this same scheme which we have at heart of promoting the more general use of electricity for all domestic purposes. I hope that we shall have a large meeting, and that the stone, once set rolling, will go on and continue, until we see what it is that is standing in the way of the more general adoption of electricity for domestic purposes. We do not expect to find any one thing, though one particular thing may predominate over others, but we expect to find out the various handicaps which are retarding the more rapid application of electricity.

Mr. Scott-Moncrieff. Mr. K. A. SCOTT-MONCRIEFF: If he could do so, I think it would be very valuable if the author would give us a representative load

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curve, not necessarily the highest of all the year, but such a curve as shows the demand upon the station and shows the reason why the plant has been installed; and it would also be valuable if he could plot out on that curve areas representing the figures he has laid before us to-night. It appears to me that that would throw a good deal of light upon the first items of the statement dealing with short-hour users. Perhaps we might find that there was not a peak for one or two hours of some 4,000 k.w. out of a total maximum demand of 23,000 k.w. I would also ask the author if he could subdivide his power and heating supply in much the same way as he has subdivided the lighting supply on a maximum demand system. Possibly this would show us the value of a low flat rate for power purposes. I think it has been stated before this Institution that a price of 1d. a unit would not pay. Mr. Lackie has proved that an average of less than 1d. a unit is a very valuable load and a paying one. I think that those figures for a great city like Glasgow might be supplemented, and it would be very valuable if they could be compared with similar statistics from Edinburgh, Manchester (which might tell us a little of the work of the Manchester system), and Southampton, which is making a most interesting experiment on supply at ½d. a unit, could give us very valuable details on that point and from the other large cities. Turning to some of the theoretical matters in the paper, I observe that the author states that the maximum demand of the short-hour users ought perhaps not to be reckoned on the expenditure of mains. I have difficulty in following his reasoning there. I think that the diversity factor is not so useful on mains as it is on the generating plant. I have in mind the circumstances of Calcutta, where we had a power load for punkas, and all day long the supply was in the city amongst the business offices. But at five o'clock we could almost see the supply moving along the feeder ammeters until it got to the residential part of the town. In that case the load factor on the mains was a poor one as compared with the load factor on the station. Another illustration of the effect of this is that it is always a great thing to supply electricity to the people of a town at all times. What is wanted is to follow them up from their offices to their houses; and if Mr. Lackie could furnish us with a curve of the tramway demand at the same time, we might see that the combined load factor was better still. It might be possible to see the effect of the people leaving their offices and getting into the cars. I have seen it in another way in Dumbarton, where the power supply shuts down at about 5.30 p.m. An engine is taken off the power busbars and put straight on the tramway busbars to take the workmen home. This question of diversity is a very important factor, and I do not agree with the author in his statement that the whole case is met by making a reduction of 16 per cent. on the cost of the maximum demand to meet the 16 per cent. diversity in the whole of the load. Manifestly the long-hour consumers do not tend to help that diversity as much as the short-hour consumers; and consequently I think the short-hour consumers should get a larger

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proportion of the difference between the total of the various maximum demands and the resultant maximum demand on the station. Another matter which I think bears on the question of the rate we are to charge is the value of increasing the total output. To-night I tried to find records of a place where the load factor had not changed, and I found that at Portsmouth in 1897 the load factor was 14·5 and in 1911 it was 14·4. The total costs in 1897 were 2·1, and in 1911 they were 1·4 on the same load factor. The output had increased from 840,000 units to 3½ million units. The cost per kilowatt on the total capital expenditure decreased from £150 to £120. If that were applied to the cost per kilowatt of the generating station the decrease would be very much greater. From what figures I could get I looked at this question so far as it relates to Glasgow. It appears from my figures that in 1897 the cost per kilowatt of the generating station was £30, and in 1911 it was £21 10s. Some figures I saw the other day tended to show that it could now be done for £12. By extending output irrespective of load factor we get these results. We cannot put in new generating plant in our stations unless we get new consumers. That is an important item in arriving at the rate of charge. I welcome the author's guidance in this paper and the practice he has followed. He has not been hidebound by the flat rate on one side, which encourages diversity to its utmost, nor by the maximum demand system on the other, which, if rigidly adhered to, encourages people unduly to prolong their maximum demand; and I think that his solution is a very happy one. It is a means towards the great end of making a universal charge for at least all domestic and small users of electricity. I would like to point out that this question of diversity is a very unusual one in this way. The maximum demand is a thing we have to pay for; we have to pay for the plant; but if we can get diversity we get something for nothing. We then get people to use plant which would otherwise be idle. If, on the other hand, we encourage people to use electricity at times unnecessary to them, the community at large is a loser.

Mr. Ruthven-Murray.

Mr. E. T. RUTHVEN-MURRAY: Mr. Lackie's tariff is a little difficult to follow, although the net results, if I read the table at the end correctly, are very easily arrived at. He urges that "simplicity must be aimed at in every method of charging," and the result of his simple tariff, as shown in columns 12 and 13 of the table at the end of his paper, is that against a "profit" of £35,490 must be set a "loss" of £31,884, the balance to the good being something like £3,605 on the total supply. If the number of consumers can be taken as equal to the number of meters, it would appear that a loss was made on the supply of 7,343 consumers out of 20,700, or on about 35 per cent. of the supply in the Glasgow undertaking. A tariff which secures such results may be very popular. I think, if I were one of the many being supplied at a loss, I should think I was being very well treated! But, after all, is this tariff of Mr. Lackie's so very simple? It is difficult to ascertain how he gets at the individual consumer's maximum demand. I see on page 152 that "in all business premises maximum demand indica-

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tors are erected except in those premises where the supply will not be used for anything like 2 hours per day." It must necessitate considerable care being exercised to find out which of the consumers are likely to use their supply for less than 2 hours per day. Then, "in theatres and large works recording ammeters are used." I should like to know something about those recording ammeters. I suppose they are only left in temporarily in order to get results. If that be so, his experience may be similar to that of others of us who have ascertained the maximum demand of consumers by observation from time to time. For instance, in 3-phase supplies in which the demand is not sufficiently large to warrant putting in, say, a Merz type of indicator, we frequently determine the maximum demand by taking instrument readings. If we happen to drop in unexpectedly a few days after taking these readings, we generally find something different—the demand has not generally decreased. I suppose that is human nature, because I must not suggest that consumers are not all strictly honest! Further, it would appear that the maximum demand in domestic premises is estimated by having "a maximum demand indicator or recording ammeter connected in the feeder or main supplying a hundred or more tenement consumers at one time," or "a recording ammeter is used for fixing the lighting demand in the larger houses." Does the author arrive at the individual maximum demands of the smaller consumers? If not, by what means is he enabled to ascertain the proportion of 3d. units to be charged? Having obtained the maximum demand, the units have to be separated into 3d. units and 1d. units according to the little table on page 154, and this must complicate the preparation of the accounts and add very materially to the time taken and cost of producing them. Those who favour the author's methods must remember that in Glasgow the proportion may be totally different from what it should be down here. In the early nineties, when I was engineer at Aberdeen, a large number of consumers took no supply whatever during the six months in the middle of the year. From the fact that I have played tennis at half-past ten at night it will be understood that it is not surprising that very little artificial light was required in many business premises and offices.

On page 149 the author sets out the five factors on which the cost of producing electrical energy depends. There is another factor as important as, at any rate, four of those he has set out, and this is the *size* of the consumer. The size of the consumer has an important bearing upon the cost at which he can be supplied. The influence of this factor is shown in the charge per consumer on page 155. There the author points out "there are at least three charges which can be treated very largely as per consumer, and not as per kilowatt," and then he refers to the capital cost of the "branch." I presume he does not refer to the service line, because if I remember rightly, in Glasgow the consumer has to fix the little box for the reception of the cut-out and meter just inside the forecourt wall, and then pay for his own service line—at any rate that used to be the case.

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The fact may have some bearing on the low cost of 7s. per annum given just below as the amount of these special charges, which are said to include the capital cost of the meter and the cost of reading the meter, rendering the account and maintaining the meter. I have looked very closely into these costs for some time, and find these items, comprising interest on cost of service (including depreciation allowance), interest on the cost of the meter, the cost of reading, changing, and overhauling the meter from time to time, and the preparation and collection of accounts, amount to no less than 24s. per consumer in many undertakings. I know some undertakings in which it is even higher than that. As this is strictly a charge per consumer, it is evident that before we can supply a single unit to a consumer, or cover any standing charges upon the supply, or get any profit, we ought to receive 24s. to cover these out-of-pocket expenses. It is because of these "per consumer" charges that it is so unfair to divide the total maximum demand in proportions according to the individual demands of the consumers and charge them at the same rate. Such a division is manifestly wrong. What ought to be done is to charge the consumers on a graded scale. We must charge the small man at a higher rate than the large man, not only for the reason I have given, but also because, as Mr. Scott-Moncrieff has pointed out, as the undertaking grows the capital costs fall so rapidly. The earlier people must necessarily have paid a higher rate, but when an original consumer adds to his installation heating and cooking apparatus, and, say, doubles his custom, he ought to get a reduction in rate, so that he shall share in the lower costs resulting from the bigger station. That is a most important point, and one which it is very difficult to deal with. It is not easy to see by what means we can charge each consumer at a different rate per kilowatt, depending on his size, but an instrument has been devised whereby it can be done, and in an exceedingly simple manner. Any instrument which enables that to be done will, I believe, prove itself of use in connection with electricity supply, and greatly assist in helping to solve the tariff problem both by simplifying the tariff and by ensuring that each consumer is charged at the lowest profitable figure.

In conclusion, there is a question I should like to ask. At the foot of page 155, in referring to this new system, the author says: "Over 500 consumers have installed electrical apparatus of some kind. One hundred of these domestic consumers' accounts, examined at random in different parts of the city, show an increased consumption of 21 per cent. as compared with the corresponding period of the previous year. This represents 7 per cent. increased revenue." What was the effect upon the load factor?

Mr. Seabrook.

Mr. A. H. Seabrook: With the general principles of the paper I am in entire agreement. There are so many people who are even now satisfied that a flat rate is possible under modern conditions for residences that to hear anybody advocating a differential rate of any kind is most gratifying. After the above main point is settled there are

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one or two points of minor importance to be considered. For instance, in the last three lines on page 148 the author makes this rather important statement: "Were it not for the consumer who gets his energy at 1·7d. per unit, the charge would need to be increased from 3½d. to a much higher figure." This means that the 3½d. consumer is being supplied below cost at the expense of the 1·7d. man. That is really a most important point if it is realised, and shows that with the differential rate we must have an alternative flat rate, and in my opinion that alternative flat rate ought to be high. I do not believe there is any need for a flat rate of less than 6d. a unit, otherwise we are doing exactly as the author says here. The consumer who is using the supply for longer hours with a better diversity factor and getting a low rate is, in spite of that low rate paying more than his share of the fixed costs of the undertaking than should be charged to him. Page 149 seems to me to be rather an apology for the short-hour consumer. I do not think any justification is needed for supplying him below cost. It is practically impossible to charge the short-hour consumer what he really costs, but I do not believe in charging any consumer at a flat rate of 3d., 4d., or even 4½d. I think that is where a high alternative flat rate comes in, and even at 6d. we are probably charging him 2d. or 3d. less than we should. But we must have a flat rate—there is no question about that, that is to say, if we want to get business. As the author says, the advertising effect of the short-hour consumer—incidentals one might say—can go against the increased cost. But we cannot justify the short-hour user being charged below cost on account of depreciation, or antiquation, or obsolescence, because plant "antiquates" and depreciates just as much whether it is running or standing idle, whether it is being used one hour a day or twenty-four hours a day; the depreciation of electrical plant goes on at practically the same rate all the year round. With regard to the maximum demand system, it puzzled me for a considerable time to know what the author meant by his statement at the bottom of page 150. Although he has put it, if I may say so, in rather an obscure way, I think he means that if we add up the total maximum demands of our consumers, then add up our total on the power station, the maximum demand indicator system does take note of the diversity of the load, because the maximum loads of the consumers are not the same as that of the power station, so that indirectly it gives an idea of the diversity. With regard to the author's system—the 3d. units and the 1d. units for additional output—that seems to me rather a vague method, but I do not take any exception to that. So long as it brings in remunerative business I do not care how vague it is. But there is one point I should like to mention. I can quite see how a man should be treated who has been on the mains a year and had so many 3d. units for lighting. We can go to him and say, "For your additional units in the future, over so many at 3d. you will only be charged 1d." But I do not see how we can go to a new consumer who has only been on the mains a short time, or a man who is only partially using electricity for lighting, and put such a proposition to him. It seems to me very difficult to go to him with a

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proposition of that sort, unless Mr. Lackie assesses the lighting maximum demand, and in that case we are all very anxious to know his basis of assessment. There is one point which has not been mentioned by previous speakers, and that is as to a flat rate based on the consumer's previous maximum demand. We charge a man 6d. and a 1d. on the maximum demand system, and then we find his average rate is 3d. We take that as due to his load factor and say, "Now we will take away the demand indicator and you can have all your units at 3d." That argument is fallacious for this reason. Directly we take away the demand indicator we remove the inducement to a man to keep down his maximum demand. He immediately "flares" away without any regard for maximum demand, and his load factor immediately decreases, and he ought really to be paying 4d. or 4½d. instead of 3d. On page 158 the author rather seems to think that an eight-page pamphlet on tariffs is excessive. In the present state of the art I believe that the more rates we have the better we are likely to get on. The more rates I can get my Committee to pass the better I am pleased, because the more rates and systems I have to dangle in front of the consumer the less likelihood there is of his escaping; whereas if I have one or two cast-iron rates which I cannot alter, and no alternatives to give, and I have to say, "You must take it or leave it," very often the man leaves it. If we have sixteen or twenty different rates to put before him it is very strange indeed if we cannot get him on one of them.

Mr. Buckell.

Mr. L. E. BUCKELL: I should be very much obliged to the author if he would clear up this point, as to how he arrives at the demand for each individual consumer. That is important from several points of view. If the demand is arrived at by means of demand indicators, then the capital cost per consumer is going to be increased, and other complications will come in. If it is going to be assessed, we are all very anxious indeed to know how the assessment is arrived at. Another point I should very much like to know is, whether this tariff of the author's is intended to apply to all his consumers, or whether, as the title of the paper suggests, it is simply intended for domestic consumers. It is perhaps interesting to note on page 149 that the different points which, as the author shows, bear on the cost per unit of supplying electrical energy, may be grouped into three divisions. The first item (the maximum rate at which the supply is demanded) practically means the plant in the station; the second (the number of Board of Trade units taken) affects the consumption of coal, and is entirely a running cost item; the third (the time of day at which the demand is made) again affects plant in the station, and is a capital item; the fourth is also entirely a question of capital charges, while the fifth refers to the very important question of the decreasing capital cost as the total number of consumers supplied increases. I am very pleased to note that Mr. Lackie has mentioned on page 149 the question of mains. It has always appeared to me that in considering load factor we are practically only considering plant in the station, whereas a very large amount of the capital of any undertaking refers to capital spent in

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ways quite other than plant. Such things as mains and office expenses of various sorts are really not affected by load factor to a very great extent. It comes to this, that the amount of output is at least as important a thing as the load factor at which the electricity is sold in its effect on profits earned. In considering the profit from any particular consumer, or class of load, that principle I think is getting very much overlooked in a good deal of this discussion on tariffs. It is a principle that applies to every commercial undertaking—that the bigger the business done the cheaper one can sell, quite irrespective of any other condition whatever. That appears to apply quite equally to the sale of electricity. I see that Mr. Lackie is another apostle of expediency. I think all of us are getting to see that this question of expediency is probably the biggest question to be considered in determining the exact details of the form of tariff upon which we are going to sell electricity on a big scale. As Mr. Seabrook said, we cannot make a cast-iron tariff which is right theoretically, and then expect to sell large quantities of electricity. With regard to the remarks on page 152 on the subject of domestic load especially, I am very glad to find that the author, who is supplying in one of the biggest towns of the kingdom, appreciates the question of this smaller domestic load. We have taken out a few figures recently in Newcastle, and have estimated that we have only 10 to 15 per cent. of the possible domestic load. As we are looked upon as being rather successful with private-house consumers, there is evidently an enormous increase in revenue to be obtained. The gas company, which is now making the bulk of its money from domestic supply, have a revenue which is six or seven times as much as our total lighting revenue. That shows what great figures we have to play with if we once get on to the domestic load at a proper tariff; and the tariff can well be a cheap one, because the increased load will make the cost of supply low. I was very much interested in Mr. Lackie's table, but there is one rather obvious question that arises from it. Does Mr. Lackie contend that his undertaking would have been better off if he had not supplied several thousand consumers, who are shown as incurring a loss on the undertaking? I can hardly believe that is so If these consumers do not mean a loss on the undertaking then the table is perhaps a little misleading. I do not see myself how any consumer, except a very exceptional one, can involve a loss on a large undertaking, and I should like to hear what the author has to say on that point. Then on page 155 the deduction is that the author does not charge for his meters, and I would like to know if that is the fact. This 7s. per annum for the maintenance of the meters, etc., is met in most undertakings by the charging of a meter rent. As a consequence these items of capital cost, which may be treated as per consumer, are met by the consumer. Mr. Seabrook has already asked what I intended to ask with regard to page 156, namely, what the object is in taking this demand over 100 domestic consumers, and how that helps in arriving at the demand per consumer. It would also seem from the paper as if Mr. Lackie uses a

Mr. Buckell. great number of recording ammeters. If that is the case, I should be glad to know it, because they are rather expensive things if they are constantly being put in and taken out.

Mr. Cridge. Mr. A. J. CRIDGE: I want just for a moment or two to refer to the table given by Mr. Lackie, from which it will be seen that the profit on the domestic consumers is represented as 5·8 per cent., while the profit on the power consumers is represented as 1·32 per cent. It seems to me quite certain that if the author has in mind the benefit of the domestic consumer, he can still afford those consumers greater benefit than they at present obtain. The County of London Company charge 5½d. a unit, and I consider the load factor for a domestic installation, which is used up to half past 11 or 12 o'clock at night, is sufficient to warrant a very much lower price per unit than that. The fact is that in most cases the profit on the power supply is very small indeed—sometimes it vanishes—while the profit on domestic lighting is out of proportion altogether. On page 155 reference is made to the reading of the meter and the cost of rendering the account. If we employ a man at 30s. a week to read meters, he can read, say, 80 to 100 meters a day, so that the cost per reading would be about ¾d., which comes out to about 9d. or 10d. a year. It seems to me there is a lot to be made up before we get to the 7s. that Mr. Lackie speaks of, and I would like him in his reply to give a little definite information as to where that money goes to.

Mr. Burnand. Mr. W. E. BURNAND: Whilst only indirectly concerned with tariffs to any extent, I cannot help feeling strongly that unsuitable tariffs and restrictions are at the present time holding back the industry from a great expansion, and I feel sure that these can be modified to remove present obstructions. It seems to me that the great fault with present tariffs is that they do not sufficiently coincide with the cost of production, with the result that the use of electricity is unnecessarily restricted many times when this is no benefit, but only a source of loss of revenue to the suppliers, and at other times the supply is not sufficiently restricted when this would be of great benefit to the suppliers, thus requiring a larger plant than would otherwise be needed, this preventing a cheap supply. On this question of tariffs I agree with the author that we cannot ignore the pioneer work of Mr. Arthur Wright, and I think that the principle outlined by Mr. Wright, that load which causes a disproportionate outlay on plant should be charged at a higher rate, with a view to keeping down this unprofitable outlay, is the correct one. Based on this acknowledged correct basic principle, however, I do not see how a much more incorrect system could have been developed than that employing maximum demand indicators on consumers' premises, and basing the high rate charge on monthly readings of these indicators. The broad objection to it is, that for every unprofitable unit that is choked off, probably a hundred or more profitable ones are choked off, in addition to the oft-quoted difficulties of getting customers to appreciate a system usually not understood by the suppliers. For these reasons, a rigid adherence to the system is

Mr. Burnand.

usually not desirable, and Mr. Christie's adaptations provide, I think, valuable suggestions for central station engineers. I do not quite see the object of the tables on page 148, since these are only correct with no diversity factor—a condition that obviously does not obtain at the present time, neither is it desired or likely to occur in the future—so that the results are not likely to be agreeable even approximately with the actual financial results. This, of course, only emphasises what the author states at the bottom of page 151, but I think that an approximate estimate of actual financial results would be more informative. Column 14, at the end of the paper, showing a loss of £31,884, based on demand, must be a long way out. If all this load was done away with, how much better off would the undertaking be? The chart, Fig. A, is based on data, placed at my disposal by Mr. Feddon, showing what load has been carried by a large generating system supplying an industrial town (Sheffield), and the total length of time the load has been above or below any given value during the year. This, I think, is what Mr. Scott-Moncrieff wanted to see; it shows in a striking manner the large proportion of time during which much of the plant was standing idle, and the serious handicap of having to carry a lot of spare plant as a sort of insurance against trouble, with extraordinary peaks that occur only once or twice a year, with a margin for a specially long, heavy fog, that may or may not occur at all. The curve represents the output over quite a normal year, and no doubt similar characteristics would be shown by plenty of other towns. Over 95 per cent. of the revenue-producing load lies below the point marked X, and if we could be sure that this load would not be exceeded, the plant need not have been extended beyond the line N. That is, all the plant indicated by the distance N to C is needed to cope with the almost insignificant (as regards revenue) part of the curve above X. In view of this, it is quite evident that this top part of the curve is no use to the producer, and looking at this, it appears doubtful if this would pay at even 10s. a unit. This sounds an exaggeration, but part of this load does not last on an average 3 hours per year, and some may not come at all for two years, but all the same the plant has to be there, in case the conditions occur which give rise to this load. This is the first point I want to make clear: that control must be obtained over this peak, so that it may be avoided, if the supply is to be cheap. The next point is, that the greater part of the normal peaks lie below the point X, and this, I think, shows where the demand indicator system fails badly. With a plant capacity of C, or even of N, what is the good of spending a lot of money buying and looking after a lot of maximum demand indicators that are all the time an inconvenience to the customer, and a source of loss of revenue all the way below the point X? It may be said with truth that it reduces the curve above X, but I do not think this compensates for the reduction below this point; and also I do not think the reduction above X is all that is imagined, since it is hardly to be supposed that this extra peak is due to half the consumers having doubled their maximum demand, but it is the result

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rather of normal maximum demands abnormally overlapping, which, of course, the indicators take no account of. Another point I want to

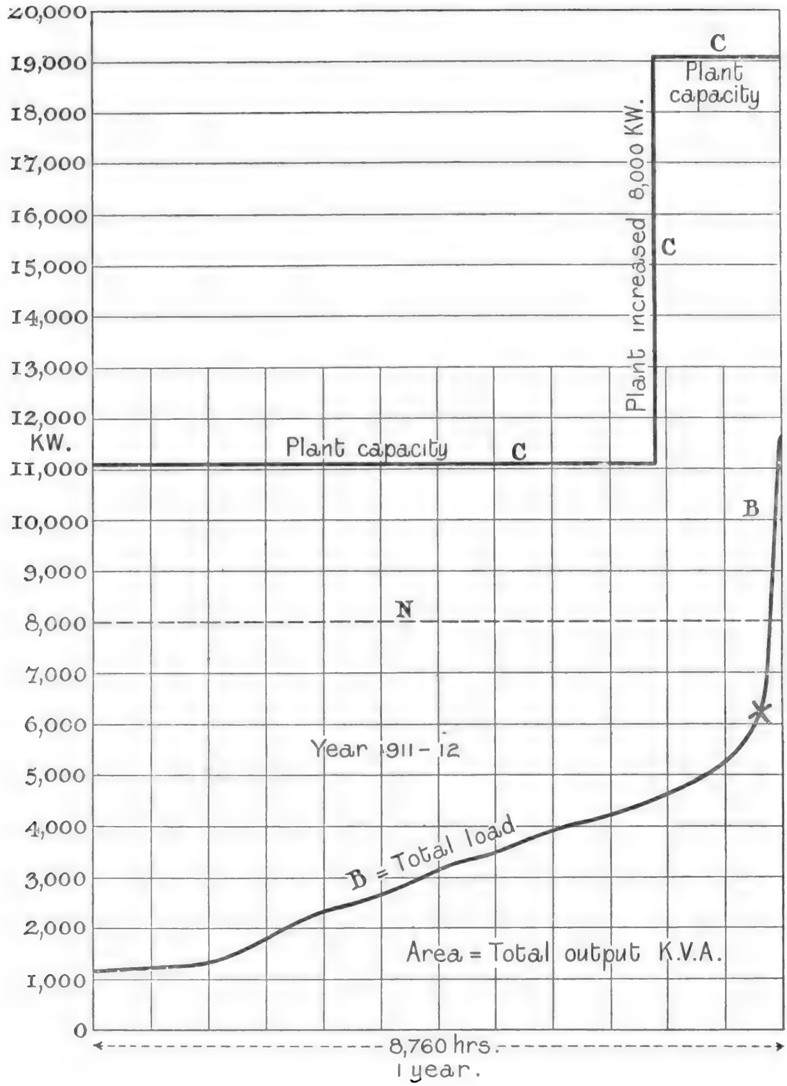

Fig. A.

bring out is, that additional load at any point of the curve below X, even peak load, is almost equally profitable, provided it does not increase the load above X, and that all is equally grist to the mill, and

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costs not a penny more in plant on these small peaks, any more than if in the valley. I do not wish to imply that merely peak load up to the point X should pay no more than absolute non-peak load (say midnight to 5 a.m.), but rather that this latter should be allowed to go right through the day if desired without extra rate, except at the odd times when the load approaches the point equivalent to X. Still with reference to the curve B, the whole of the output below X can be equitably dealt with by means of a fixed charge, based on the actual fixed costs of the service, plus a low rate per unit. I think the fixed charge should be practically equal to the net cost to the suppliers, and that the profit should come on the rate per unit. If the fixed charge is based on the actual cost, this will not be the same for 10-k.w. demand for lifts as for, say, a 50-hour per week load, due to the diversity factor being much greater with the former, so that a schedule for, say, three or four different classes is necessary. The part of the curve above X should, in my opinion, be done away with by bringing this under the control of the suppliers, and I think the way to do this is, when the load approaches a fixed ratio of load to plant capacity, say, 85 per cent. of plant capacity N, to put an extra 3d. to 5d. per unit on all load, and let the consumers know it is on. This leaves it open to the customer to leave on any vital load, whilst taking off load that can be readily spared for the hour needed to get over the abnormal hump, thus having the effect of keeping this down with the minimum of inconvenience, not comparable with the reduction in cost, made available by this arrangement. The method I propose for this comprises an additional dial, which might be added to existing meters to register the additional high-rate charge, this dial being made to register only at and above a fixed ratio of total load to plant capacity. The same means that controls the extra dial should also be available at any part of the circuit, to actuate an indicator showing when the high rate is in force. The best method to adopt to work this indicator and mechanism remains to be proved, but it is quite certain that it can be done. A pilot wire is an obvious but very expensive solution. A low voltage between one main and earth is another possible solution in some few instances. On an alternating-current system a small direct-current current may be superposed to act on a polarised armature actuating the extra dial mechanism and indicators, but this would not be effective through a transformer. The demagnetising effect of the alternating-current current can be substantially neutralised by a short-circuited copper ring near the magnetised armature. Another way might be to superpose through a series transformer, a small, high-frequency ripple on the main current-wave, actuating a little electromagnet in series, with a condenser of such capacity as to resonate at this high frequency, whilst being little acted upon by the normal frequency. On direct-current systems a small alternating current may be superposed. A series transformer, or a coil inductively near the coils of the meter, would have a current induced by the alternating-current pulsation, which could do the extremely light work needed to move an indicator or pro-

Mr. Burnand.

perly arranged meter mechanism. Most of these methods are cheap compared with what is saved in plant, so that it should be worth while to press meter manufacturers to develop one or more, as the system just described is the only one that restricts the use of current at the time when required, and encourages full use at all other times, thus combining lowest costs with maximum convenience to both user and suppliers. The bills rendered under this system would be very simple, comprising a fixed charge and units at low rate, and occasionally units at high rate. The system is obviously applicable to all classes of service, industrial or domestic, and remains automatically correct with the variations of load factor, which we must expect with developments in lighting, and the use of electrical energy, the natural trend being for lighting to come down as efficiency is improved, and for other uses to go up. I hope to try out some of the foregoing methods of control in a few months, but there is no reason why others more directly concerned should not do so also. An average tariff with this arrangement would be as under:—

Charges for Electrical Service.—1d. per unit, plus 3d. per unit at times of specially heavy load, when this reaches 85 per cent. of the plant capacity, plus following service charges:—

Requiring Meter Capacity of	
¼ k.w.	Blocks of houses where ground has not to be opened to put in service in more than one place for six houses, 2s. 6d. monthly, with 7½ units per month free.
¼ k.w.	Ordinary houses or services, per quarter, 15s.
½ k.w.	Ordinary houses or services, per quarter, £1.
1 k.w. and over	Houses or services, per quarter, £1 per kilowatt on our nearest standard suitable meter size.

Variations in above rates: Where, owing to special circumstances the cost of service is not normal, special rates will be quoted dependent on the cost of supply. Further variations: Intermittent usage where current is only used for periods not exceeding 5 hours per week, service charge is one-third the above. Power used between the hours of 9 p.m. and 7 a.m., but cut off at other times, service charge is one-third above list. Large users pay schedule rates above up to 4,000 units per annum, with a discount of 25 per cent. on all units over 4,000 per annum, with a further discount of 10 per cent. on all units over 100,000 per annum. The free units render a meter unnecessary when obviously the consumption will not exceed the allowed units.

Mr. Snell.

Mr. J. F. C. Snell: An analysis of Mr. Lackie's table is interesting, and I have been amusing myself by taking out the ratios of columns 13 and 14. I think the figures that I propose to read out to you will bear out the contention of Mr. Seabrook that a higher price should have been charged for the 1-hour consumers. For instance, on the 1-hour consumers and less there is a loss of 70 per cent.; then in the next grade of one hour and under two hours there is a loss of 6 per

cent., and then there is a profit which successively grows from 35 per cent. to 36 per cent., 46 per cent., and 60 per cent., up to five hours and over. On the domestic rate there is 46 per cent. profit, and on the churches and theatres, as one would expect, there are losses of 36 per cent. and 24 per cent. respectively; on the power and heating a profit of 9 per cent., and in the special agreements 32 per cent. I think that shows that for the 1-hour consumer certainly a higher rate ought to be charged. But that, I take it, is not the point we are discussing particularly to-night. What we are trying to do is to devise some means for popularising electricity and for capturing the supply for domestic purposes. I prophesy—and I think we would all prophesy—that the day is coming, and coming rapidly, when the supply for domestic purposes will become an accomplished fact. Only a few years ago we were very much criticised because we dared to hope that we were going to supply power. What has happened? We are supplying power by increasing amounts, and a beginning has already shown itself in the supply for domestic purposes. I know that some of the companies in the Metropolis are now beginning to feel the effect (only in a small way admittedly) of the demand for cookers and for different small domestic appliances. In many places current for cooking and heating is supplied at 1d. a unit. I have been making a little test in my own house quite recently where I have to pay 2d. for heating, and there is no doubt about it that, compared with the cost of gas there, the radiator is cheaper. I have not got to the cooking stage yet, but that I hope will follow. We may take it as a sign of the times that there is an increasing demand now for electricity for heating and cooking purposes, and what is required for the moment, even more perhaps than a tariff, is increased publicity. Although I am an old municipal man, I cannot help putting down the comparative slowness in the growth of the supply of electricity for domestic purposes to the fact that the supplies have been in the hands of the municipalities hitherto. I have a very great respect for municipal people, but they were not able at first to deal with it in the commercial way that companies are able to do. But they are now getting alive to their shortcomings, led by such men as Mr. Seabrook or Mr. Couzens, and some of the energetic engineers of the municipal undertakings. So that I again prophesy that, within the next five years, we shall see a marked improvement in the supply of electricity for this particular purpose. If that does take place my contention is that the tariff can take care of itself, because the increased plant that will be necessary will be obtained at reduced capital charges. One of the deterrents at the present moment is that the older plant cost very much more per kilowatt than new plant costs to-day. Time will cure that, and the increased output will take care of the establishment charges, so that all these things will react, and the increased output and perhaps the better diversity factor will all bring about a simple tariff; and a simple tariff will again react upon the output for domestic purposes. Of course I can quite understand that undertakings which are now struggling to

Mr. Snell.

Mr. Snell. give this supply must devise expedients, ways and means, to bring it before their different consumers, but they are only expedients; and I say emphatically that the growth of the demand itself will bring with it a simple tariff and the reduction of cost which will enable electricity to be supplied to consumers for all purposes. I think we ought to thank Mr. Lackie particularly for one thing in his paper, and that is for the admirable analysis that he has made of the diversity factor in Glasgow. We had that discussed here a few years ago in great detail. That, to my mind, is the thing about which we know least at the moment, and if the engineers of some of the different undertakings would make more careful analyses of the diversity factors of the different classes of consumers we should get such information together as would enable us to make deductions, and to frame for the time being tariffs which would bring about the best economical results. Once that stage is reached, then I again say that the increased output which will follow will bring with it a reduced and simple tariff, as simple really as the tariffs for gas supply. I hope that other engineers in other parts of the country will help the Institution, and help the industry, by publishing similar information for their districts. This would give us valuable matter from which we should be able to make useful deductions.

Mr. Chamen. Mr. W. A. Chamen: With the exception of Mr. Scott-Moncrieff, all those who have spoken to-night, I think, are dealing with supplies in large cities, and I would therefore just like to put forward rather a different kind of case. Take South Wales. The South Wales Electrical Power Distribution Company have only recently begun to work an Electric Lighting Provisional Order there. Owing to the operation of the Eight Hours' Act the power load, which is the bulk of our business, is more or less steady from 6 a.m. until between 2 and 3 p.m., and then it drops very considerably. Lighting, therefore, does not produce a peak as it does in the cities which have been spoken of, because we have comparatively little lighting at present. Our load is a power load. Therefore we are in the position of being able, if we care to adopt that policy, of taking on a lighting load at scrap prices. It is just an inversion of what we have to deal with in large cities. Now there are some villages in South Wales where there is no gas at all, and I think it will be agreed that there are chances in these combined circumstances of making some sort of success of electric lighting. We have been successful in arranging so that there are practically no underground distributing mains for lighting purposes; they are all overhead along the streets, and with overhead mains the cost of the services is very small. Even under these favourable conditions the electric lighting of cottages does not advance as rapidly as it ought to do, and the question of free wiring in one form or another must be faced. With the object of reducing the cost of supplying large numbers of small consumers we got out the following scheme a year or two back, but it has not yet been put into operation. Let each cottage be wired for any number of lamps the consumer requires, but supplied through some device which shall limit the maximum demand

to a certain value, either by dimming the lights or by fluctuating them or by cutting off the supply when that value is exceeded. Let the supply be taken from the street-lighting circuit, which is switched on and off automatically by clock-switches at dusk and dawn. Let the consumer be given to understand that except in case of illness or other emergency he is not to keep the lights burning from 11 p.m. to 4 a.m., and that if he does so he will have to be supplied by meter or under some different arrangement. Then the price to be paid can be calculated with sufficient accuracy without the necessity for putting in a meter at all. In the particular case in point it worked out at 1s. per week. The scheme was to collect the revenue weekly in advance by means of collectors provided with receipts and, perhaps, bell-punches after the manner of tramway conductors, thus reducing book-keeping work to a minimum and being sure of making no bad debts. If the collector could not get the 1s. he would cut off the supply and go away. It would presumably be possible to arrange for some satisfactory check upon the revenue, as the tramway people do upon the collection of fares. Such a scheme, particularly if combined with free wiring, might work well, but it has the serious drawback that it makes no provision for the use of electricity during the daytime for cooking and other domestic purposes. It is for this reason particularly that I have been so much interested in hearing what the author had to tell us. We find in these small houses where we are supplying for lighting through meters that flat irons and such things are coming into favour, although we are charging them at the lighting rate of 4½d. In another district for which we have applied for a Provisional Order there is as yet no gas at all, but if we do not do something to encourage the use of electricity in the daytime for cooking and heating the gas people will want to come there. What we want to find out is how to prevent them from coming there. Mr. Chamen.

Mr. ARTHUR WRIGHT: In addition to the five factors mentioned by the author which govern the cost of supplying electricity to consumers from a power station, I consider that one of the most important is the number of years remaining of the concession to supply electricity, as no one can expect companies whose lease of life is very short to charge on the same basis as those municipalities who do not labour under this serious economic mistake of the Electric Lighting Acts. This great handicap has very often been overlooked in making comparisons between the charges of supplying electricity by these two very different classes of undertakers. London affords the best instance of the necessity for this discrimination, as here, owing to the threatened absorption, on the terms of the Electric Lighting Acts, of the existing undertakings by the London County Councils in 1931, all new capital that will have to be put into these undertakings during the next 19 years will have to bear an extraordinarily heavy rate for redemption unless some authoritative pronouncement be very soon made giving a better protection of this new capital than the terms of the Electric Lighting Acts promise. Another important factor governing the cost Mr. Wright.

Mr. Wright. of supplying energy, which the author has not included in his list, is the total generating capacity of the power station. Recent years have proved that the cost of supplying electricity diminishes enormously with the growth of a power station up to about 40,000 or 50,000 k.w. In reference to the losses shown on the author's worked-out Profit and Loss Account for the Glasgow undertaking, I should like to point out that owing to the above-mentioned reduction of costs the losses are not quite so bad as the analysis would seem to indicate. This is proved by the author's statement that the average cost of all his increase of business during the past few years, including capital, came out to less than 1d. per unit. This remarkable result of installing large and modern turbine plant at Glasgow seems to be a justification for now not attempting to rectify the grossly unfair division of charges between short- and long-hour consumers so vividly illustrated by the author, as it seems to indicate the inexpediency of raising a consumer's charges if his annual bill exceeds the total cost of supplying him from modern plant, however unfair the present tariff may be to the good-load-factor consumers.

Mr. Eck. Mr. Justus Eck (*communicated*): For central stations which have been running for several years the domestic tariffs should be arranged so that the consumer is not required to bear the expense and convenience of a double wiring system to enable him to use electrical energy for heating and small power applications. The 800-hour bi-monthly estimated hour demand system—say, for short, the Lackie-Glasgow system—seems excellent for domestic consumers, and necessitates only a minimum of capital expenditure: one meter, one double-pole switch, no demand-indicator, and a simple bill. Every city has not such uniformity of residence, or uniformity of demand as Glasgow, and in other towns it is certainly advisable to have other systems of charging equally understandable to the consumer. The double-tariff meter enables the consumer with the same house wiring to enjoy both power and lighting rates, determined on the basis of an estimated maximum demand agreed between consumer and supplier from time to time, and varied at the consumer's wish. Take Mr. Lackie's 6 R + K house, and with, say, the following lamp connections:—

Dining-room	60 watts
Sitting-room	90 „
Three bedrooms	120 „
Kitchen	60 „
Offices	60 „
	390 watts

and allow for, say, 250-watt flat iron, and 120-watt fan, and, say, a 200-watt heater. If the consumer agrees to take a maximum demand, say, of 250 watts at the rate of 60s. per kilowatt per annum, he would pay 15s. fixed charge, and then 1d. per unit for current used. The supply would, in order to receive 65s., have to sell 50s. worth of 1d. units, *i.e.*,

600 hours. The consumer would be able to use his current as long as he liked at 1d. per unit, plus the basic charge of 15s. per annum, provided he did not overstep the 250-watt maximum; a double-tariff meter with a clear-showing indicator, or even coupled to a bell, would tell him when he had overstepped his agreed maximum and gone on to the 6d. rate. Such a system encourages the use of electric irons, fans, etc., during the day, and the use of, say, bedwarmers at night when the lighting requirements are less, and while permitting a good illumination in the house for all ordinary requirements, allows of extra festive illumination charged at the higher rate only during the time of abnormal demand. If the flat-iron, ventilating, or cooking load is greater than the maximum demand as it is likely to be in the smaller houses mentioned, then a separate power circuit could be used, and the double-tariff meter connected in such a way that the heating units would be charged at the rate of 1d. as long as no light was used, at the 3d. rate when both were used simultaneously, and the lights at the 1d. rate as long as the agreed maximum demand was not exceeded. Simplicity in tariffs is desirable more for the central station than the consumer, who very soon learns what pays him best; it is the case of the man who has difficulty in making his time-sheet correctly, and yet understands exactly the value of racing odds. Mr. Eck.

Mr. E. W. COWAN (*communicated*): I will not repeat the arguments which I put forward in the discussion on Mr. Seabrook's paper, when I attempted to prove that the maximum demand system as a determinant of price was scientifically unsound. The same arguments apply, however, to Mr. Lackie's paper. Both Mr. Seabrook and Mr. Lackie contend that the maximum demand system is fundamentally sound, but that it is expedient to depart from the system for commercial reasons. I hold a contrary view, namely, that the maximum demand system is fundamentally unsound when treated as a determinant of price, though its influence should always be taken into account; and I hold that it is, nevertheless, sometimes expedient or politic to use it as a determinant of price, because of the appeal it makes to the sense of justice of those who have only given superficial consideration to the complex subject of pricing. I will confine my comments on this occasion to the use Mr. Lackie makes of the word "loss." In the "Memorandum" at the end of his paper he tabulates certain "losses" made by the undertaking for the management of which he is responsible, which losses aggregate £31,884 6s. 6d. I submit that the word "loss" is an inaccurate word to apply to this figure. It is not possible to say whether it is a loss or a profit without further information, but there is a strong presumption that it is of a profitable nature. A simple illustration will make the point clearer. Assume that an undertaking is supplying for lighting purposes one million units at 4d. per unit, and that the receipts just balance the expenditure so that neither a profit nor a loss is made. Assume also that the conditions of supply are such that if the output could be doubled the cost per unit of production would be reduced by 25 per cent., namely, from 4d. to 3d. Now, suppose that a factory Mr. Cowan.

Mr. Cowan. offers 2½d. per unit for another million units, the load factor, etc., being the same as that of the lighting supply. Should this offer be accepted or refused? The cost price per unit with this additional supply will be reduced from 4d. per unit to 3d. because the output will be doubled, but this consumer only offers 2½d. per unit. Mr. Lackie would say that the undertaking would make a loss of ½d. per unit by the transaction, but let the calculation be made as follows :—

	d.
One million units at 4d.	4,000,000
One million units at 2½d.	2,500,000
Total revenue	6,500,000
Less cost at 3d. per unit	6,000,000
Profit...	500,000

Thus a profit of 500,000d., or £2,083 13s. 4d., is made out of supplying a million units to a consumer at ½d. per unit "loss." If Mr. Lackie had given what is sometimes called the "Law of Central Station Costs," that is, the relation between cost and output for his undertaking, it would have been possible to have ascertained whether the amount which he classes as a loss to the undertaking was really a loss or whether it was, which seems probable, a profit. The author of a new book entitled "The Laws of Supply and Demand" sent me some of his advance proofs a few days ago, and I note that he refers to the "loose thinking" of electrical engineers upon this subject of pricing. He refers to the "mixed ideas prevalent" among electrical engineers, particularly upon the "necessity of taking the cost of production as the main determinant of price." It must be admitted, I think, that we deserve this somewhat severe criticism from outside experts. I have held the conviction for some time that the progress of electricity supply is seriously hindered by the refusal of engineers to pay regard to the science of the subject of pricing a public utility.

Discussion before the Scottish Local Section on 13th February, 1912.

Mr. Starr. Mr. D. A. Starr: So far as the small lighting concerns in which I am interested are concerned, I may say that we have found it good policy to adopt very similar lines to those mentioned in the paper. There are, however, one or two points I would like to ask further information on. On page 149, where the author gives five examples in connection with the cost per unit, I think he could have added another one as the sixth and put it this way: "On the capital outlay for the supply to the consumer or consumers." On page 151 I think that the diversity factor should be taken a little more into consideration, especially for a city load. Mr. Lackie mentioned losses on the 1-hour consumers who use a very small amount of current. The distributor has the capital expenditure to make in each case, and it is hardly fair to the distributors that they should not receive something near an adequate

return on that capital expenditure, especially when we take into consideration maintenance, attendance, and meter reading. I am sure the author has many consumers who run at a loss—this is shown by the table, and even under the new arrangement there will be a number of consumers who bring him a small revenue and really cause a loss. That could be got over by adopting a minimum charge or nominal minimum charge within the powers that are given to authorised distributors under the Electric Clauses Act. This could be modified to meet the case of tenements, churches, offices, and shops. I think that the sum of £2 per annum spread over the different quarters could be advantageously adopted. The next item which I have briefly noted here is on page 155, where the author mentions 7s. per annum as the cost of maintaining a meter, reading it, and rendering the account. I think in the case of two meters in the same premises this need not be doubled; 50 per cent. more would possibly be sufficient for an extra charge, or, say, 10s. 6d. instead of 14s. On page 156 he mentions what may be a very good suggestion from the undertaker's point of view, but I do not think we could all agree with the author's plea for a withdrawal or reduction of the rates of any trading department even if it be for the benefit of that portion of the public who consume electrical energy. I am of opinion that such a department or business should pay its quota to the carrying on of the common services of the city. I would also like to ask the author if since the introduction of his new system of charging to domestic consumers he has found any differences in the load factor at the power station. Mr. Starr.

I notice that the author refers to the Edison Company of Boston. Now quite recently Mr. Selfridge, who is a friend of Mr. Insull, the chairman of the Chicago Edison Company, told me that the lighting and power supplies given by this company in Chicago were cheaper than any other supplies given in the world. From the information I got on my recent trip to Canada and the United States I found that, on the whole, the charges there were higher than the rates we have here either in connection with companies or municipalities. In Ottawa they have a system, which is found in various parts of Canada, whereby they charge so much per square foot of space in a house, excluding, of course, verandahs and such like. They charge 2d. per square foot, plus 3½ cents. per unit consumed. It seems to me an extraordinary method of selling power, but the people over there do not object to it. Big power supplies, such as the Hydro-Electric Commission of Ottawa, sell power in bulk to local supply authorities, who distribute it over the city or their authorised area. The rates charged to the distributor are on a basis of so much per horse-power per annum, and the amount of power for the whole twelve months is calculated on the top momentary peak, taking, say, in December or January of each year. There is no averaging, and the distributor after transforming and distributing the bulk supply charges on similar lines or on the total amount of apparatus connected. While this is all right for the generating concern I do not see how the consumer finds it beneficial.

Mr. Mavor.

Mr. SAM MAVOR: The author says on page 149: "It could be reasoned that the mains laid would not have been appreciably diminished in extent if office lighting had not been demanded." I do not quite see the application of this to such a city as Glasgow, where the mains in a large proportion of the centre of the city must be laid primarily for supplying offices. Near the bottom of page 150 he again says the maximum demand system "does recognise the extent to which the aggregate maximum demands of the consumers do not occur simultaneously. In other words, it does recognise distinctly whether or no any individual consumer takes his supply during those hours when the maximum demand is being made by the mass of the consumers." It does not seem to me that the individual is recognised, but rather he is grouped with his class in considering his maximum demand, so that an individual consumer whose maximum demand does not synchronise with the peak load of the station does not have recognition.

Mr. Maccall.

Mr. R. B. MACCALL: The author has clearly shown that consumers nominally equal in certain respects are not entitled to claim that they should be charged at an equal rate per unit. The principal aspect of the paper, however, is not the charge for current for ordinary power or lighting, but the charge for domestic purposes. Complaint has been made recently that heads of electrical undertakings have done little towards the more universal use of electricity for heating and cooking. They are accused of sitting down and waiting for the "normal rate of progress" after having fixed a low rate for energy used for "heating and cooking." The proviso for "heating and cooking" is the weak spot. It does not matter at what price current can be obtained or how cheaply apparatus may be bought, the fact is it is impossible to persuade the consumer to run an entirely fresh set of wires, or pay further impositions in the form of meter rent, for the pleasure of using an electric kettle or iron. It is maintained that a more simplified system of charging is required, in which the additional circuit for heating apparatus will be eliminated, except in cases where the power demand is too heavy for the existing cables. Now the author in this paper has shown clearly how to get over this, and is to be congratulated on the simplicity of the scheme which enables a consumer to get all the current used for domestic purposes other than lighting at 1d. per unit, and the 1d. units shown in every account rendered instead of waiting till the year's end for what looks like (to an impatient consumer) a problematical reduction, as an abnormally low consumption in the winter months has to be made good by a large consumption in the other months of the year, which might mainly be caused by a heating demand. It will be observed from the author's paper that the encouragement given to domestic consumers has raised the average consumption of this class of consumer from 2 hours per day in 1900 to 3 hours per day in 1910–1911; and in addition there are also the heating or cooking units consumed in the same premises; the units are not contained in the figures shown. The author is on rather delicate ground when he states on page 149 that it might be contended that the depreciation on plant

Mr. Maccall.

used for 1 hour per day only should be very much less than depreciation on plant used for 10 hours per day, and he is apparently conscious of this as he puts it forward tentatively. It is very doubtful whether depreciation should be more on plant running and kept in good order than on plant left standing practically idle and probably neglected. This raises the old question of what depreciation is. Is it tear and wear, obsolescence, or a fall in market value? The question need not be pursued further. On page 150 the author says there is no necessity for supplying energy at less than 3d. per unit for lighting where the price of gas is 2s. per 1,000 cub. ft. This means that where gas is less than 2s., if competition is to be indulged in, it might be necessary for an electricity undertaking to lower its tariff accordingly, and look for economies in some direction to enable this to be done; but the other side of the question is that if the price of gas be 4s., should the price of electricity be raised to 6d. per unit simply because 6d. would be a low competitive price; or is it the duty of municipalities at any rate, if not of private companies, to sell current at as low a rate as possible commensurate with proper financial provisions irrespective of the price of gas?

I quite agree that the maximum demand system of charging is essential as a basis of all charges for current. If electricity undertakings depart from this basis they are sure sooner or later to sell current at less than cost, and if there be a large enough consumption of that nature disaster is imminent. To give discount according to quantity consumed, irrespective of maximum demand, appears also to be unsound finance, but it might be quite justifiable where the consumption is so proportionate to the demand that all lighting and power consumers are respectively about equal in their hour's use of their maximum demand, so that it would not be worth while to vary the rate of charge. This may quite well happen in a town largely residential and where there is a relatively small trading community. Incidentally with reference to page 152, and the table of charges per kilowatt per annum, there is a golden mean between charging £3 per kilowatt per annum, with 1d. per unit for all current consumed, and £7 17s. per kilowatt per annum and 0·191d. per unit. It certainly would simplify the scale of charges for power users at least if the scale per kilowatt per annum was, say, between £6 and £7 8s. with all current at 0·33d. per unit. This would make the short-hour consumer pay his just dues and give the longer hour user a substantial benefit. On page 153 it is remarked that the flat rate is based upon a given number of hours' use per annum and not on the extent of the demand. This is practically an argument for a flat rate founded on the maximum demand, which has been granted to domestic consumers, churches, and schools in Glasgow. There is, however, considerable difficulty in fixing a flat rate for shops, in that they do not have one common closing hour, and many of them have basements which require lighting all day. The doctrine of expediency has been referred to and justified. It has for some years been practised by chief engineers, but is only now being openly

Mr. Maccall.

acknowledged as an important factor in fixing prices. It is also beginning to be found out by the gas undertakings of the country. Both Glasgow and Edinburgh in connection with the hire of gas appliances have seen fit to modify their charges for hire of stoves. Glasgow has altogether ceased to charge, and Edinburgh only asks 5 per cent. on capital. The argument is used that the only effective way of fostering an increased consumption amongst present consumers and others is to supply the appliances necessary for consuming gas. Hitherto hiring out has been on a self-paying basis. Arguments like these would never have been used by gas people if the competition of electricity had not stimulated them to adopt the principle which they previously sought to cover with contempt when it was promulgated by electricity supply undertakings. Perhaps the author will explain if it is profitable to have a consumer with an account of only 12s. 6d. per annum when on page 155 it is stated that the cost of reading and maintenance of meter is 7s. per annum.

Mr. Newington.

Mr. F. A. Newington: We in Edinburgh do not believe in the maximum demand system, as the author knows. He states that it is the most suitable system of charging, but I rather think he himself has some doubts about this, as the paper tends to show. He says on page 149 that although some people only take current for ½ hour per day he does not consider they should be charged abnormal rates, and a little further down he doubts whether users for 1 hour should be charged their proportional amount of maintenance and depreciation; then on page 150 he suggests that 1-hour users might only be debited with half the capital expenditure on plant. I dare say these modifications are advisable, but they are not the maximum demand system, and I think they help to prove that this system is not commercially workable. The consumer never knows what he is paying for, and does not understand it. On page 157 the author says that although people might have been out of their house for two months, a bill came in just the same. People naturally do not like this. They want simply to pay for what they get, and object to pay for what they think they are not getting. The author's remark on page 150 that there is no necessity to sell electricity at a lower price than gas, is one that I most heartily agree with. The competition between the two illuminants is very keen, and if electricity can be supplied as cheaply as gas, there is no doubt as to which people will use. If even long-hour users do not have to pay more for electricity than for gas, why complicate matters by using a system of charging that very few people understand? Brighton, the cradle of the system, and a number of other towns, have found it unworkable and have given it up. I cannot see how the maximum demand system shows whether individual consumers use electricity at the time of maximum demand or not. As to the author's present system of charging for domestic consumers, its simplicity and the great ease with which it can be understood by every one are very strongly in its favour. The advantage of not requiring separate

wiring for heating, etc., is also a very strong recommendation. The effect of this method of charging, as stated on page 155, seems to be extremely satisfactory both to the supply authority and the user—that is, an increased consumption at a reduced rate. Perhaps if the low-priced units were not allowed during December and January it might be the means of reducing the peak. It is very doubtful whether it is advisable to encourage cooking by electricity. I suppose the majority of people take their heaviest meal of the day between 6 and 7.30 p.m. and so require the greatest amount of cooking from 4.30 to 6.30, that is, just about the time of highest load in the winter months. If this is so, it certainly will not pay to sell electricity for cooking at 1d. per unit, provided that it is used during the winter. I would like to ask the author whether he has had any trouble with people questioning their allocation of what they have to use at 3d. before they get on to the lower rate. Mr. Newington.

Mr. A. MEARS: On page 149 the author might add another item to the other five upon which he says the cost per unit depends, viz., the composition of the whole circuit, that is, the relative proportions of different types of consumers. Cities vary largely in this matter; what obtains in one does not in another. We may have one city in which the load is nine-tenths residential and one-tenth commercial, or *vice versâ*, and there is no doubt that the relative proportions of the various types of consumers make a decided difference in the cost at which they can be supplied with current. For instance, I notice that the domestic consumers in Glasgow use 10·8 per cent. of the total lighting units sold at ordinary rates during the year, whereas in Edinburgh it is in the neighbourhood of 21 per cent. Possibly as a result there is a larger diversity factor over the whole of the Edinburgh circuit. As the author states, there is no doubt that the principle of the maximum demand is perfectly sound, but I think it is open to question as to how far it is advisable to carry it into practice. He has introduced the question of expediency, and one thing that is very expedient is that consumers should have a scheme of charging which is quite simple. It is still difficult to make consumers understand maximum demand principles. The maximum demand system has been very much modified in Glasgow. Expediency has taken the form of charging for 2 hours per day of the maximum demand at a flat rate of 3½d. per unit instead of 6d. and 1d. It is an open question as to how far this modification should be pushed, whether it should not be extended to 3- and 4-hour consumers, and discounts be given to the longer hour consumers. From the table we have before us, the average price per unit obtained from lighting consumers up to 3 hours and under 4 hours per day is 3·1d.; this is practically what is charged to domestic consumers as a flat rate. Beyond the 4-hour limit we have some that are charged at an average rate of 0·975d. per unit, some at 1·571d. These represent a very small number of consumers proportionally; those from 4 to 5 hours a day represent 2 per cent., and 5 hours a day and over another 2 per cent. of the ordinary rate lighting consumers. Mr. Mears.

Mr. Mears. It is true that consumers of 5 hours a day and over consume 18·4 per cent., and 4- to 5-hour consumers 8·9 per cent. of the total ordinary rate lighting units, but in the interests of simplicity of tariffs, is it not expedient to give these very long-hour consumers, who only represent 4 or 5 per cent. of the total, special terms on their own merits and charge the remainder at a flat rate? With regard to the question of the author's new rate for domestic heating and cooking, taking the annual consumption in units for the various kinds of houses as given on page 157, I would like to ask him how much variation there is in individual cases from the average of their type. I have before me an annual return of 400 consumers in tenement houses of 3 and 4 rooms and kitchen. They are unfortunately not separated out into their respective sizes, so that I cannot compare them directly with the similar houses mentioned in the paper. In the table on page 157 "3 rooms and kitchen" houses take 120 units per annum, and "4 rooms and kitchen," 220 units per annum, or an average of 160 units per annum. I find that the average of these 400 consumers comes out exactly the same as the author's figure—viz., 160 units—but at the same time there is a very wide diversity amongst them. There is a large number consuming only 60 to 70 units, whilst others consume from 250 to 300 units. If consumers from 100 to 200 units are taken I find 58 per cent. of the 400 consumers fall within these limits. Those with from 200 to 300 units consumption represent 24 per cent., and those below the 100 units 18 per cent. This means that there is a very wide range of annual consumptions for similar sized houses—from 60 units to 300 units per annum. I should like to know if the author has found the same diversity in Glasgow. It appears to me that it is not altogether a question of the number of rooms, but more a question of the manner in which the house is used; an important factor is whether boarders are taken or not. With regard to the figure of 7s. per annum for the reading and maintenance of a meter, does this include interest, sinking fund, and depreciation? Again, in connection with the comparison of gas and electricity, I should like to know whether it is a general feeling that a 4 ft. inverted incandescent gas burner compares in a general way with what is sold as a 50-c.p. metal lamp. On this basis gas at 3s. means electricity at 2·6d., and gas at 2s. means electricity at 1·75d. It is difficult to get exact figures for such a comparison because it is largely a question in each case how the illuminant is dealt with—in other words, whether it is well installed and run correctly.

Mr. McWhirter. Mr. Wm. McWhirter: Mr. Starr said something about the loss on short-hour consumers being borne by the company. I should have thought the loss would be borne by the long-hour consumers. If the author would drop all the short-hour consumers the long-hour ones would have the benefit, but I think it is a case where expediency comes in, and although on hard-and-fast lines it might be difficult to allocate certain plant to those using the current for 1 or 2 hours a day, it would be difficult to carry on the Glasgow undertaking

without getting more and more into the methods of the gas people. We cannot depend altogether on the accumulator, but have to install plant in accordance with the demand made, still I question very much if we could satisfactorily dispense with the small consumer, even though he is run at a loss. The author has shown on page 155 that it takes 7s. to maintain and read a meter, and if interest and depreciation be added, this figure will be increased considerably. I think the new system explained on page 155, by means of which he gets rid of an extra meter and gives the consumer such a big reduction is an excellent idea. I am not at all satisfied with the figures which Mr. Mears has given us with regard to the difference between Edinburgh and Glasgow. Of course we would need to compare these figures with other centres of light and leading, but we might assume the difference in favour of Edinburgh is accounted for by the people of the capital city being more studious than the Glasgow people, and therefore keeping later hours. Mr. McWhirter.

Discussion before the Manchester Local Section on 27th February, 1912.

Mr. S. J. Watson: The number of tariffs in use up and down the country is extraordinary. I doubt whether there are two towns or two companies who are charging on exactly similar lines. This condition of affairs cannot be good for the industry, and I would therefore plead that in the future, by some mutual movement on the part of municipal engineers, joined perhaps by leading members of our own Institution, something should be done to reduce tariffs to a common basis which will be clearly understood by everybody who may use the supply. At present we may find one town or district with one kind of tariff, and another situated perhaps only a few hundred yards away with a totally different set of tariffs. Such a state of affairs is very much to be deplored. The author comes before us to-night with another new tariff, which is again rather different to anything else. The figures which the author gives go to show the enormous difference which must exist in the charge per unit to different classes of consumers, if the supply is to be remunerative. Take, for instance, the "1 hour and under" consumer. It will be seen that the revenue produced is £11,352 on a demand of 4,000 k.w.; that is to say, the average amount charged per kilowatt is about £2·3, while for 5 hours and over the average amount charged exceeds £16 per kilowatt. It is perfectly obvious that it cannot be correct to charge in one case £2 per kilowatt and in the other £16 per kilowatt. Either there is an enormous loss on the one, or an enormous gain on the other. There is a very interesting point which the author makes when he says that "the average account of the domestic consumers is shown to be £2 16s. per annum." This question of supply to domestic consumers is, to my mind, one of the most important which has to be faced. I very much doubt, however, whether with so small an income as £2 16s. Mr. Watson.

Mr. Watson. per service, the supply can be given profitably, not because of the cost of generating such supply, but on account of the distributing costs including capital charges on mains, services, repairs, meter readings and accounts, the majority of which costs depend not on the kilowatt of demand, but on the expenditure per service. The average expenditure on mains and services is usually £40 to £50 per consumer, and if we assume that half the consumers are large, and cost £80 to £100 per service, and half are small and cost only £20 to £30 per service, the capital and maintenance costs on distribution alone must be £2 to £3 per service per annum. It is clear, therefore, that we should do our utmost to encourage the domestic use of sundry electrical apparatus, so as to increase the revenue per service from small users. What we really want is a system of tariffs so arranged, that when consumers who live in different districts compare notes, their accounts will show that the charges to both are very similar, although if they take the trouble to work out the average cost per unit an appreciable difference will be found to exist. For instance, a power user may be charged 0·45d. per unit at his works, and 4½d. at his residence, and it is no easy matter to convince him that one class of supply is worth ten times as much per unit as the other. The existing systems of charging on flat rates per unit makes it difficult to give reductions by comparatively small increments. For instance, if it is wished to reduce from 3d. per unit, it is necessary to jump to 2¾d. or even to 2½d., which is equal to 8⅓ or 17½ per cent. If the flat rates are to be maintained, I suggest that the price should be 2s. 6d. for 10 units instead of 3d. per unit, and reduction could then be made in 1d. stages, say of 3⅓ per cent. at a time. Some time ago, when using demand indicators, I made a careful analysis of all our lighting consumers' accounts, and found they might be divided broadly into three classes: (1) Those who use the supply for less than one hour per day, principally offices and schools; (2) Those who use for 2 hours per day, almost entirely consisting of shops, and (3) those who use for 3 hours per day, such as public houses and private houses. I am sorry to say that in Bury we do not have any lighting consumers using the supply for 4 or 5 hours. On page 150 the author says: "If the consumers who take their supply for 1 hour and under were not connected, some of the standing charges, at present allocated against them, would have to be made up by the other consumers." I think the author, on reconsidering this remark, will agree that it is not quite correct, because it is quite obvious that if these undesirable people were disconnected, and long-hour users substituted for them, the undertaking would be placed in a much better financial position. I am very interested to note the author's remarks about atmospheric pollution. If Glasgow will initiate a movement which shall have for its object the remission of all rates on municipal and company electrical undertakings on the ground that they are in no small measure responsible for the improved health conditions of this country, there is not the slightest doubt that he will obtain the whole-

hearted support of our industry, and the greater and more expensive the fight to obtain such remission, whether successful or otherwise, the better the advertisement for all of us. **Mr. Watson.**

Mr. MILES WALKER: I do not understand why, to-day, within 10 miles of Manchester, any one should be paying 6d. per unit. Perhaps if we lived in Glasgow we should be paying 5d. and 1d. per unit after so many years. I think that where large power users are considered, a good deal of difference should be made between the charges for a good and a bad power factor. When a consumer can see that by using a better power factor he will be charged a better rate, we shall get better power factors. **Mr. Walker.**

ALDERMAN W. WALKER: It was not my intention to discuss this paper, but I am very much interested in any scheme that has for its object the getting-on to the station of an increased number of consumers, and I think there are one or two points brought out by the author that have not struck many of us, and yet are perfectly true. The first of these is the fact that the consumer in a small house is likely to give a longer-hour load than those in large houses. First for the reason given by the author, that smaller houses and tenement flats are not so well lighted by natural light, and that also on the average the occupants keep later hours; therefore, even the very small consumer with the accounts that the author has quoted are worth consideration. The next point necessary for success is that no separate wiring shall be required. I know from those who have had experience in trying to get lighting consumers now on the Manchester system to install radiators and other accessories, that immediately they are told it is necessary to incur capital expenditure for additional wiring (and I am speaking of the occupants of the larger houses), they will not listen any further to the suggestion, and they refuse to adopt electric aids in their domestic economy, yet they are just the type of consumer that would be the most advantageous to the department if they could be obtained. One of the very first things that they who secure the business for the departments will have to see to, is that the initial wiring is adequate for any additional load that may be put on; of this I am absolutely certain. There is no hope if we are going to require a double system of wiring in houses. Another thing I must compliment the author upon is his schedule of tariffs, which has certainly not been formed without guidance. There is a deep knowledge of human nature about it. Even for the business man who takes everything into consideration, it is so clear that he cannot think he is going to pay more for the lighting of his private residence than he is paying for his business place. In Glasgow, figures have been so arranged that he will have quite a different idea, and I agree with that point of view, because we are dealing with human beings; the crux of the question is to get people to imagine they are getting something very cheap at what is really an ordinary price, and they would then certainly use the supply for a long time and very often. I do not agree with Mr. Watson's criticism in regard to the table of hours. **Alderman Walker.**

Alderman Walker.

It strikes me as being an extremely strong point, this dividing of the larger-priced units over the various months of the year, rather than making them follow on to the ultimate aggregate before the reduction takes place. I think there is something very clever in this fixing of hours of normal charge, followed by this reduction of 2d. It is taking into consideration the factor of human nature once again. The other thing the author has brought before us is one that I imagine he dare not even mention in Glasgow, because there they have town councillors, and to venture to suggest to a municipal committee that they should not rate everything and everybody is something we in England dare not dream about. I do say that the way in which municipal supplies are being treated by the demand for aid to rates is very wrong. We find some municipalities spending large sums of money on their Health department, and in support of Smoke Abatement exhibitions and sanatoria, and yet they will raid the Electricity department (which can do more than all the other sources combined), year after year for a huge subsidy to the rates. I think we who are engaged in municipal work have a very hard battle to fight on this question.

Mr. Cooper.

Mr. W. COOPER: The tabulated statement will be very useful if at any time we wanted to get out similar figures for our department. There are, however, one or two things I am not quite clear about. The author states that there is no necessity for extra wiring for radiators, etc. First, I would like to point out in the case of installations wired for metallic lamps the wiring would not be strong enough for radiators, although it might be all right if the installation had been put in for carbon lamps. Then again, if we put a radiator on the lighting circuit, the demand indicator will be affected unless we wire beyond the indicator; that is, unless I have read the paper wrongly, and he is going to put on recording ammeters instead of a demand indicator. If we have to buy a recording ammeter for every installation it sounds rather fearful. Mr. Watson mentioned something about making a standing charge high enough for everybody. It seems to me that if we are going to keep strictly to the standing charge in case of selling power at rates of ¾d. to ½d., the running charge will have to be down at the third place of decimals (£5 per kilowatt is practically ½d. per unit based on 50 hours per week, 50 weeks in the year). I find the trouble with demand indicators is that they very soon get out of adjustment, and the demand is shown to be greater than it actually is. For that reason I have practically abandoned the use of them, although I try to stick to the demand indicator system. They are principally used for public houses. This class of consumer is always comparing notes, and then those who are charged with a higher demand want to know how it is that their accounts are charged at a higher average rate than the others, so I have put them all on a 3 hours' basis, which I found was the average for this class of property. With regard to private residences, I find, especially in the larger houses, that they average less than 2 hours, instead of 3, as stated by the author. Mr. Watson mentioned the

difficulty of reducing the price of current, even ¼d. per unit being too big a jump. I think the better way to reduce the charges is to work with discounts, say 2½, 5, or 10 per cent. for prompt payment, and at the same time getting the money in sooner. Mr. Cooper.

Mr. C. C. ATCHISON: Mr. Miles Walker mentioned the question of power factor in regard to power consumers. There is no doubt about it, if we are to get alternating-current supplies working and fairly large loads taken, the power factor question is going to be a serious one for station engineers. I think it would pay engineers to have some method of controlling the motors on consumers' premises. If we consider the ordinary provisional orders under which we are working, we have a pretty restricted control, and although probably in Manchester they can put a heavy hand on people who do not follow their ideas, yet with smaller local authorities we are going to have trouble. As to the question of double wiring, it is a thing which I agree should be got rid of if it can possibly be done, but in getting rid of it we are up against the question with regard to controlling the wiring again. Alderman Walker says we should control the wiring and see that it is suitable for the conditions to which it is to be applied. We know perfectly well that those conditions are varying day by day. I think Mr. Cooper said that with the old carbon filament lamps there was a larger load to carry, but now that metallic filament lamps are used we are able to get a smaller amount of current carried by wiring, which can, in addition, be used for taking any radiator put on the system. If those radiators are going to be of any material use to the supply undertaking's revenue, it is necessary that we should see whether they are not going to grow out of all proportion to the original wiring. I think that municipal authorities ought to have much stronger powers to control the wiring of premises in their districts, and to see that it is carried out in a manner suitable not only for the present conditions but for future extensions of consuming devices. We want to push cooking and heating, and if we are to do it by separate batches of wiring, it is simply going to be that we shall not get it at all. Mr. Cooper mentioned with regard to large houses that he did not agree with Mr. Lackie's figure of 3 hours. Our private house consumption is about 2 hours. I am very pleased with Mr. Watson's suggestion with regard to selling electricity. It does seem hopeless, when we are selling at so much per unit, to reduce the amount. It is no good giving a man a tenth of a penny. If we are to give him ½d. we cannot afford it, so what are we going to do? For this reason I agree with Mr. Watson's idea—if only we could deal with larger units it would be much better. With regard to discounts, the idea seems to be that they should be based on the number of units consumed. I do not agree with this. The people who deal with the bills only understand £ s. d.; they do not understand what units are, and they do not care. The consumer, if an ordinary business man, is also able to understand and appreciate the discount better. If we look into a comparison of accounts for consumers having the option of a maximum demand indicator system Mr. Atchison.

Mr. Atchison.

and a flat rate, it is seen that with a discount on quantity the consumer paying the lowest average price per unit also is liable to get a larger discount; in other words, the effect is cumulative, and I consider discounts on the amount of the bill is better. With regard to the maximum demand system, I shall be very pleased to see all my customers on that system gradually get on to the flat rate, and I have this in mind when considering any revision of the prices to be charged. People readily understand the flat rate, but the maximum demand indicator system is not easy to explain so as to be clear to the ordinary consumer, and is seldom remembered if understood at the time, the consumer generally having the higher price in his mind, and feeling somehow that he is being "had."

Mr. Sells.

Mr. F. S. SELLS: In my opinion there is no doubt that the way in which the author has gone about to arrive at his method of charging must be considered commercially sound, because he has arrived at the only way of solving the problem of the small consumer. Whatever method we employ for charging for electricity, we cannot get away from the fact that we must study the consumer's pocket, and the greatest difficulty in doing this in the past, especially where corporations were concerned, has been the fact that the accounts at the end of the year had to be open to severe scrutiny. The giving of "special" terms to light consumers has been in most cases out of the question, therefore the maximum demand system on the lines devised by the author seems to solve nine-tenths of the difficulties we are confronted with. Mr. Watson's objection that there are too many tariffs already, and that we do not like to think of a new one appearing upon the scene, can hardly be taken seriously, because the fact that there are so many tariffs shows that there is not one of them a really good one, otherwise it would have been accepted more generally, and I, for one, agree with the author that if this method could be employed more generally, a greater demand for current for domestic purposes would arise.

We see from the author's tables that his average private consumer's bill is £2 16s. per annum, and he tells us that his consumers cheerfully pay it. It may be all right from a station point of view to say, "We want £7 or £8 a year from a consumer before it can pay us to bring our mains to him," but if they want £7 or £8 they cannot get it. They must either do without the consumers and cripple for ever the popularisation of electricity for domestic purposes, or they must come down to the author's way of looking at things and be satisfied with a yearly revenue of £2 16s. per house, which is still more than a man would have to pay for gas, but the difference is compensated for by the greater advantages electricity offers. Mr. Watson says that the station would be better off without the £2 16s. per annum consumer, because the current supplied to these people at, what he terms, non-remunerative rates, might be more usefully employed to serve large manufacturing concerns. I venture to entirely disagree. At the time that the £2 16s. consumer wants his current the works are shut down, and we have it on the authority of a number of engineers that they find

Mr. Sells.

it impossible to get sufficient of the consumers with the high load factor. The main point, however, which we must not lose sight of is, that if it is absolutely necessary to charge a man £7 or £8 per annum for his domestic electricity, it is out of the reach of the majority of people. If a central station succeeds in catching enough of the small fry, it is bound to pay in the end, and I even go so far as to say that until the paying point is reached, a station engineer has the perfect right, for the sake of popularising his undertaking, to sell to the small people at a non-remunerative figure, and to let the big consumer pay slightly more for it. In most cases, after all, the small consumer in a private house in the suburb is part and parcel of the big consumer in the city, and if an engineer has to run a commercial undertaking, he must have the right to adopt a commercial attitude, and on this point alone the author's paper should be instructive to all of us. There is one point, however, which is not quite clear to me, and that is, how the author recommends his colleagues should arrive at the maximum demand of each consumer. Where one has a large experience it is comparatively easy to work out a man's average demand and deal with it as the author has done—that is to say, if the consumer has been on the mains for some time—but how does the author recommend that newcomers should be dealt with? I do not quite believe the little tale about the recording ammeter, and I think the author could tell us a little more on this point if he wished to do so. I have found that in many cases the failure of a maximum demand system has been due to the way in which it was handled. In most cases the methods adopted are contrary to the consumers' interest. If our station engineers set out to popularise electricity they must be more generous in their methods. In fixing the maximum demand for any particular consumer, the station engineer should take into account what kind of lights are fixed in the house, not how many. They should certainly not include in the maximum demand the lights fixed in cellars, closets, halls, cloak-rooms, etc. They are only on for a short time occasionally, and consumers should be encouraged to put lights into such odd places and use them freely and not be frightened off. Lights in these positions, whilst consuming very little current, are the greatest convenience in a house, and therefore the finest advertising medium for electricity. If the station engineer can afford to go a step further, he might treat plugs for small heating and cooking utensils in the same way.

Mr. Wilkinson.

Mr. H. T. Wilkinson: I think the author has done quite the right thing in devising so simple a tariff. While the maximum demand system is technically correct, it is a mental impossibility for the consumer, and the sooner that is realised the better. The simpler the tariff the better for all concerned. The basing of tariffs on the maximum demand system, without actually indicating the maximum, and merely taking it as an arbitrary figure based on the lamps installed, is purely a tax on installation, which is wrong. Some of the power companies in Switzerland charge so much per lamp per annum without

Mr. Wilkinson.

any unit charge whatever. This, of course, is very simple, but not perfect. I have often wondered why, in the case of flats, blocks of small houses, offices, etc., a flickering device should not be installed in each consumer's premises, and a charge made on the demand at which the flicker operates, without any unit charge; it would practically amount to a rate such as is charged for water. We can use as much water as we like, except being penalised for waste; but we do not waste much as a rule, and I do not think the waste of electricity would be serious. It would in any case not matter very much, as it is much more important to keep down the maximum demand on the peak than to reduce the actual units consumed off the peak. This system would considerably reduce the capital cost, first by keeping down the maximum demand on the station, and secondly in the consumer's premises by eliminating the meter, except one for the whole building. It would also reduce the running expenses in reading meters and maintaining them, which the author mentions amounts to 12½ per cent. of the cost of supply to the domestic consumer. We should also get a very good load factor in the accounts department, as the accounts could be made out for some time ahead quite accurately, instead of there being a rush at the end of each quarter. The disadvantage of this scheme, I quite admit, is in the fact that it would not be feasible where heating and cooking apparatus are installed, and separate circuits would have to be provided; but the rooms occupied in such buildings would be all contiguous, and a separate circuit would not be an expensive matter. In the case of corporations and supply companies some kind of tariff is essential for light and small power; but where it comes to large power users it is a question of getting the best price we can, and to simplify matters it is very often necessary to create a tariff for each individual consumer. I have known cases where consumers have been charged quite in their own language as it were, such as a weaving-shed at so much per loom per annum. Another case, where the consumer ridiculed the price of 0·9 of 1d. per unit, a much better price was obtained by an annual charge based on the horse-power-hours which he was firmly convinced would be consumed on suction gas at $\frac{1}{10}$ of 1d. each. To be successful in obtaining and retaining consumers it is essential that the tariffs must be of the simplest character, and such as they can quite well understand, and I think that the author has realised this thoroughly in the tariff which he advocates.

Mr. Cramp.

Mr. W. Cramp: I should like to refer to one or two points that have not been mentioned. In the first place, there is the question of limit of supply area. It seems to me that while we all wish to avoid the multiplication of tariffs, yet it seems rather unfair, considering the figures which the author gives with regard to capital cost in the case of lighting, that a consumer who is 5 miles from a centre of supply should get a rate like that of the man in the centre of the city. I also notice that there is no central station engineer here to-night who has said anything about special rates. It is a point which comes out very strongly in the

author's table, in which I see special agreements are mentioned for a consumption of 1,714,693 units at 1½d. per unit. It is quite clear from this that the large consumer is not, in Glasgow, encouraged to the same extent as in some municipalities. Does Glasgow never cater for the large consumer who can give a good load factor, or are such men in Glasgow willing to pay 1d. per unit? On page 150 the author states that "there is no necessity to supply electrical energy for lighting at less than 3d. per unit in a town or district where the price of gas is 2s. per 1,000 cub. ft. or more." I question whether this is the fairest way of looking at things. It may be human nature, but for how long is electricity to be tied to the price of gas? Does not such a hint suggest the possibility of collusion between the chairmen of the gas and electricity committees? I need only say with regard to the author's references to the smoke problem, that I believe, when both electricity and gas are obtainable at reasonable prices for domestic purposes, that the amount of smoke in the neighbourhood will be much reduced, and I think it is high time that Manchester made a move in this direction. There is a point on page 153 which is a very ingenious one. The author has apparently discovered the constancy of load factor for domestic purposes. It is on this that his tariff is based. I suppose other engineers must have discovered it, but they have not used it in the same way. I agree entirely with those central station engineers who say that separate wiring for power and light must be abandoned. How is a man who is putting electric light in a house which he has taken for 3 or 5 years to afford to put in two sets of wires? it is not reasonable. As an alternative, I would suggest that electrical apparatus, such as radiators, etc., should have a small Coulomb-meter attached to each piece of apparatus, which could be read by the ordinary meter man. Such an addition would not be at all expensive. The argument which the author uses on page 154, viz., the allocation of a proportionate number of lighting units to each of the two monthly bills, is very cunning. But it also seems to me to be commercially sound and reasonable, for it is clear that a large part of the cost of 1 unit is due to capital charges, which naturally should spread themselves evenly over the whole year. On page 155 the allowances for holidays seems to me to be a little excessive. I cannot shut my house for two months in the year. But possibly in Glasgow citizens can take life more easily. Mr. Cramp.

Mr. W. W. Lackie (*in reply*): In reply to Mr. Scott-Moncrieff, Fig. B gives two load curves for each of the two years 1902 and 1912, which I think show the reason why the plant was installed up to 24,000 or 27,000 k.w. These curves have also been marked off so as to show the consumers under one hour, those above one hour and under two hours, etc. To sub-divide the power and heating consumers at present would be useless as the number is so far insignificant, but I hope to be able to do this next year. I understand that Mr. Newington, of Edinburgh, has analysed the domestic consumers' accounts in the same way as I have done, and our figures agree very closely. The diversity factor referred to by Mr. Moncrieff does not exist in Glasgow. The maximum Mr. Lackie.

Mr. Lackie demand for tramway purposes occurs at the same time as the maximum demand for lighting purposes, but the combined load factor is better than either of the individual load factors. This is accounted for by the fact that at the breakfast and midday meal hours, when there is a depression in the private power demand due to works shutting down, there is a peak on the tramway demand.

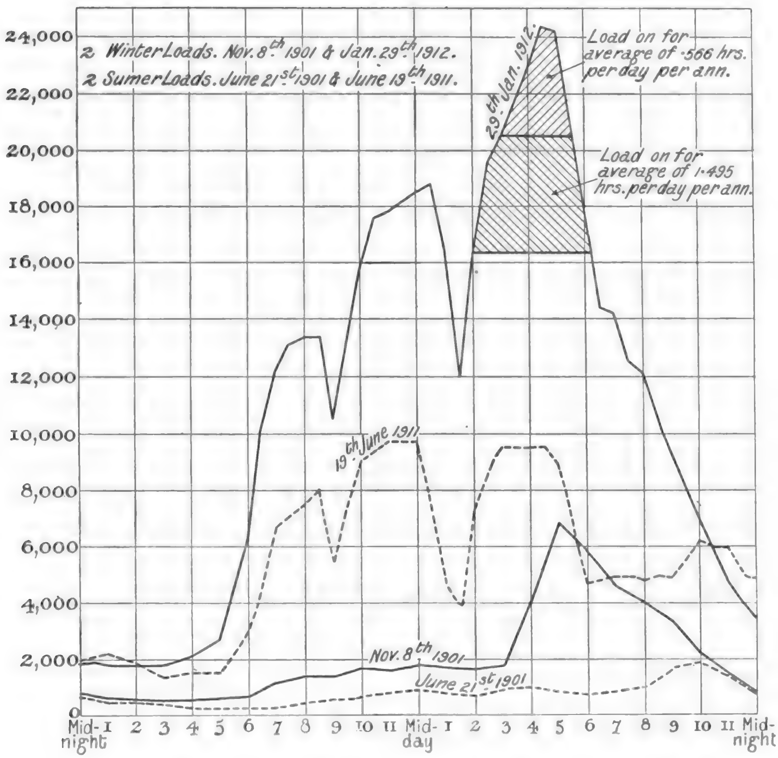

FIG. B.

In reply to Mr. Ruthven Murray, I have said that for many years our system of charging was 6d. per unit for the first 365 hours and 1d. per unit thereafter. We increased the figure of 365 to 730 and reduced the initial price from 6d. to 3½d. per unit. From previous obtained results and consumptions, we knew where demand indication could be removed, *e.g.*, in premises where the consumer did not use his supply for anything like two hours per day. The simplest way of arriving at a domestic consumer's maximum demand, so as to give him the benefit of the penny rate for energy used purposes other than lighting, is to take the average year's consumption and divide it by 800. The result-

Mr. Lackie.

ant figure is the demand in kilowatts. In Glasgow we can get 100 flats of the same size, 4 rooms and kitchen or 6 rooms and kitchen as the case may be, and by counting the total maximum demands of these, we base the average on the actual demand of the 100. There must be some allowance made for different parts of the city. I know that in Aberdeen and Glasgow there is daylight till 10 p.m. in summer, but it is dark at 3 p.m. in winter, so that although the number of hours of darkness in London and Glasgow is the same, the division of the hours of darkness is different. There is one other factor to be kept in view in connection with the supply to domestic consumers. In Glasgow we have a large number of tenements or flats, so that each branch supplies six or eight consumers. This reduces the cost of services very materially. It means that if a branch costs £4 or £5, the actual cost per consumer is £1. We have, in addition to this, stair-lighting for these flats, which brings in a revenue of £3 per annum per stair. As a matter of fact, the average number of consumers per branch over the whole city is 3·3 and the number of consumers per branch in residential areas is 7, and it will be appreciated that this is very different from what obtains in districts composed of self-contained houses. This meets Mr. Murray's point that no consumer pays whose account is less than 24s. Mr. Arthur Wright wrote to me on this subject, and I have looked into it with the following result :—

FAIR ANNUAL SERVICE COST PER CONSUMER.

	£	s.	d.
Interest, sinking fund, and depreciation on cost of laying service 8 per cent. on £4 6s. 6d. ...	0	6	8
(If 7 consumers are supplied off one branch, this cost is reduced to 11d.)			
Meter 8 per cent. on £2	0	3	2
Testing and changing meter	0	3	0
Surveying meter	0	3	0
Collecting	0	1	0
Stationery, printing, etc.	0	1	0
General establishment charges	0	3	0
Total	1	0	10
If 7 consumers were supplied off the same branch, the charge per consumer would be	0	15	1

The average maximum demand of the domestic consumers is 0·22 k.w. The average revenue per domestic consumer is £2 16s., and it will therefore be seen that 15s. is only a small proportion of this. We have met our large consumers by reducing the number of hours' use of the maximum demand. Our rate to a consumer whose maximum demand is, say, 200-k.w., is 2,800 hours' use at the initial rate and all above at a lower rate, whereas to a consumer whose maximum demand is

Mr. Lackie. 2,000 k.w., we charge only 2,250 hours at the initial rate. I think this entirely meets another point raised by Mr. Murray. The effect of adding the heating load cannot yet be ascertained. Our load factor is rather better than it was in the previous year, and this would tend to show that the heating rate is not less than a 20 per cent. load factor.

In reply to Mr. Seabrook, I must say we have found very little trouble in fixing the maximum demand of all our consumers, and we have had very few complaints. In the case of the older consumers we either had their maximum demand before heating apparatus was installed or we had a neighbouring house of the same maximum demand. Where there seemed anything abnormal in the account, the matter was looked into and a recording chart taken at the house in question. I have said that the balance sheet is not to be taken as strictly accurate. No charge is made for meter rent, and consequently the 7s. charged for reading and maintaining the meter has to be accounted for.

Referring to Mr. Buckell's remarks, I think I have made it quite clear that I did not contend that the undertaking would have been better off if we had not supplied several thousands of consumers who show a loss.

In reply to Mr. Cridge, the cost of one meter includes the salary of the surveyor, ledger clerk, rendering and collecting account, and repairing, testing, and installing meter. I gave full details of this charge in replying to Mr. Starr's remarks. The meters are read twelve times a year, and the accounts rendered six times a year. Each surveyor has charge of some 2,000 meters. Mr. Cridge further raised the point about the percentage of profit and loss on domestic consumers and power consumers. I would point out, however, that if a lower rate per unit for coal used for power purposes is allowed, the percentage of profit on the power supply will be very much more than on the domestic supply. It may be of interest to state that prior to the adoption of the modified rate, the power companies around Glasgow endeavoured to give one rate to each consumer depending upon the amount of apparatus he had in his house: if a man had nothing but lighting he was charged 5d. per unit; if he had one or two radiators the charge might be reduced to 4d.; and if he had a large amount of heating and cooking appliances the rate might be as low as 2½d. This was found, however, to give dissatisfaction alike to the consumer and the company, and the Glasgow system has since been adopted.

Mr. Burnand objects to the tables on page 148 because they do not allow for any diversity factor. I do not think that that is the proper way to look at it. The figures are relatively correct. You can either take it that they allow both for a diversity factor and a relatively lower capital cost per kilowatt, or that neither have any diversity factor.

I was very much interested in Mr. Chamen's remarks. I can remember when he was in Glasgow that it was my duty to explain the maximum demand system to many consumers, and I came to the conclusion then that the man who did not get the advantage of the

Mr. Lackie.

lower rate seemed disinclined to understand the maximum demand system, whereas the man whose account contained many penny units understood the system quite readily! It is generally the consumer who pays the higher rate all through who complains most, although as has been shown he is the less profitable consumer, if he is not quite unprofitable.

I realise the point Mr. Arthur Wright has raised about the lighting concession and the size of the installation. It is a most difficult thing to prove that any individual consumer can be supplied at a profit, and in fact it would be easy to show the opposite. The extra units generated in Glasgow for the last few years have cost under a penny, including capital charges, partly owing to our having lowered our rate of depreciation in face of the rate of sinking fund having been increased.

Mr. Cowan's communication is extremely interesting, but I do not agree with his illustration. In the first place, I think that the statement that "the maximum demand system is fundamentally unsound although its influence should be taken into account," is contradictory. The simple illustration given is also not convincing. I do not see how a 25 per cent. reduction is to be made on supplying the second 250,000 units if these additional units are to necessitate additional plant, mains, and of fuel, oil, etc. It is manifestly unfair to the first consumer to charge him 3d. and then to charge the second consumer 2½d. Mr. Cowan will admit that if the first consumer went off the mains the second consumer would require to get his price increased, but over and above this, such practice as Mr. Cowan suggests is prohibited by the Clauses 19 and 20 of the Electric Lighting Act of 1882, which makes it obligatory on the part of the undertaker to supply electricity to persons in similar circumstances on the same terms. Clause 20 prohibits the making of such agreements as will give undue preference to any person. If a person does not know what the cost of producing any given article is, he is not in a position to quote a price for the sale of it; and I maintain that the cost of production must be the determining factor in fixing the selling price of electrical energy as it is in fixing selling prices generally.

I agree with Mr. Starr that another factor in deciding the rate of charge is the capital cost per kilowatt. This is really the first factor and the basis on which the others are to be raised. I assumed that this was understood. A minimum bill per consumer may be desirable, but it leads to irritation on the part of consumers. A minimum bill, and meter rents were a distinct source of grievance, hence we dropped both some years ago. The item of 7s. for repairing meters, reading them, and rendering accounts is made up as follows:—

	Per Annum. £		Per Meter. s.	d.
Salaries of surveyors	3,100	=	3	0
Salaries of collecting department	1,137	=	1	0
Repairs to meters	3,100	=	3	0

Mr. Lackie. Our load factor has increased during the past year, but I am unable to say by how much this is due to our new domestic rate. That the load factor has not decreased is satisfactory.

Mr. Mavor is correct in stating that the term "group of consumers" would be better than "individual consumers" when referring to the maximum demand taking cognisance of the hour at which the demand is made.

Mr. Maccall's criticism is most satisfactory, for the actual working of the Glasgow method has fallen on his shoulders. I consider that if a municipality, which is supposed to sell energy at cost price to each consumer, is in a position to charge a slightly higher rate than cost to a consumer for lighting, and is so enabled to offer a slightly lower rate than cost for another form of use of the current to the same consumer, it is justified in doing so when the object is one of such importance as air purification. The account of 12s. 6d. per annum to houses of one room and kitchen, with 7s. for meter charge, can be justified. The balance left for current is 5s. 6d. Taking the rates of £7 8s. per kilowatt, plus ¼d. per unit, we have for one lamp one-thirtieth of £7 8s., which equals 5s. and 24 units at ¼d. (a farthing) equals 6d. Alternatively taking the charge at £3 per kilowatt and 1d. per unit for current, we would have one-thirtieth of £3 = 2s. and 24 units at 1d. = 2s., a total of 4s., against the 5s. 6d. available.

Mr. Mears' remarks are most interesting and valuable, and I have to thank him for them. The odd consumers who are above or below the average struck by the Glasgow scheme are dealt with in the paper, and the larger consumers and similar houses with boarders are likely to use the supply for more than 800 hours per annum and so are entitled to the extra consumption at a lower rate.

Mr. Newington says that the maximum demand system is unpopular even in Glasgow. My experience has been that the consumer who gets on to the low rate understands the system readily, and the consumer who does not get on to the low rate and does not deserve to get on to the low rate, does not want to understand the system. I agree that the revenue from churches is almost found money, and this is a case where expediency must be applied, because according to the maximum demand system church supplies would appear to be unprofitable. The loss shown in theatres and halls is, I feel sure, due to the maximum demand made by the halls. These public halls are not lit throughout the whole year, and even in the winter months are not occupied as theatres are, but against that they are undoubtedly consumers who come on after 6 p.m. Applying the maximum demand system in Glasgow undoubtedly means that the consumers at present get the amount of the standing charges on some 4,000 k.w. of plant divided amongst them on account of consumers not coming on during peak load; this must amount to about £16,000.

In reply to Mr. Watson, it is distinctly desirable to have approximately the same rates and methods of charging in the same district, and I am glad to say that in Glasgow, Govan, and Partick, and in

Mr. Lackie.

the areas supplied by the Strath-Clyde Company and the Clyde Valley Power Company the rates of charge are all very much alike. It is quite true, as Mr. Watson said, that some consumers only pay us £2 3s. per kilowatt, while others pay us £16 per kilowatt; but the point is that the consumer paying £16 per kilowatt gets his energy at 1·5d. per unit, and does not complain, and the consumer who only pays £2 3s. per kilowatt does complain, and thinks he is overcharged at 3½d. per unit. It is true that the average domestic consumer's account is £2 16s. per annum, and it may be difficult to prove that any one individual consumer is profitable, whereas the analysis shows that domestic consumers as a class are profitable. The alternative for charging so much per 10 units, so as to give a wider range for a small reduction, is to alter the number of hours' use of the maximum demand at the initial rate. For instance, I would suggest if any reduction was being made on the 3½d. units, that we should reduce our rate from 730 hours' use to 700 or 650. There are many of the standing charges allocated at present against the 1 hour-and-under consumers, *e.g.*, interest, depreciation, and sinking fund on land and buildings, rent, rates, and taxes, and similar charges, which would still exist if such consumers were disconnected.

In reply to Mr. Miles Walker, it is true, as he says, that a consumer having a bad power factor should, on account of the high proportion represented by mains in our capital costs, pay a higher rate per unit than a consumer with a high power factor ; but if it is difficult to explain the maximum demand system and the meaning of the load factor to the ordinary consumer, it would be much more difficult to acquaint him with the significance of the power factor.

I am glad to assure Alderman Walker that the Glasgow Corporation has never taken profits from the Electricity Department for the relief of rates.

In reply to Mr. Cooper, I am of opinion that there is a very great deal of house-wiring which will stand a considerable amount of heating and other appliances being attached to it without danger. If it is remembered that nearly all the wiring work in domestic premises was carried out for carbon filament lamps, and with conductors made to stand 1,000 amperes to the square inch, it will be seen that there is little or no danger in connecting one or two radiators. As a matter of fact, we always send an inspector to examine the wiring of any house where we are notified that they wish to take advantage of the rate for energy to be used for purposes other than lighting.

In reply to Mr. Atkinson, the number of appliances connected in residences in 12 months amounted to 900. It is obviously impossible to have a fixed price for electrical energy all over the country, or even a fixed principle of charging, with so many varying rates of interest and sinking fund, and with such a variety of supplies in different districts. Mr. Wilkinson suggested the system of having a fixed charge per kilowatt, and allowing consumers to use what they liked. This would undoubtedly lead to abuse.

Mr. Lackie. The proposal by Mr. Cramp that the rate of charge should not be the same all over the city, but should be lower to those consumers who are near the generating station, owing to their requiring a smaller capital expenditure on mains, seems to me to be iniquitous. The generating station must be put down where the energy can be generated most economically, and the consumers nearest the station might easily be the most unprofitable ones. With reference to special agreements, the analysis in the paper shows that it is immaterial whether these consumers paid for 730 hours use at 3½d. and all further quantity at ¾d., or got the whole of their energy at a flat rate of 1½d. per unit. Mr. Cramp also raised the interesting point as to whether it was not possible to have collusion between the chairmen of the gas and the electricity committees in order to keep up the prices of gas and electricity, I consider that if a municipality is in a position to sell energy at cost. price to each consumer, and charges a slightly higher rate than cost for light, thus being enabled to supply the same lighting consumer under cost for electricity for purposes other than lighting, such a municipality is justified in doing this, so long as the price over all for the energy supplied is not above cost.

SPECIFICATIONS.

By FRED. S. SELLS, Associate.

(Abstract of paper read before the MANCHESTER LOCAL SECTION *on 13th February,* 1912.)

This paper is not intended to teach members of the Institution how to draw up specifications. It is merely a few notes and criticisms on the subject, and deals particularly with debatable points with the object of eliciting full discussion. The views expressed in the paper represent the author's own personal opinion, and they refer to one particular branch of electrical engineering only.

It may be of advantage to try and establish the legal meaning of the word "specification."

HALSBURY'S "Laws of England" says:—

> "A Specification is a DETAILED description of building, engineering, or other works executed, or proposed to be executed."

BALL, on "Law Affecting Engineers," says:—

> "A written description and plans, more or less complete, defining the methods of construction, etc., to be used, prepared by the Engineer for the approval of the Employer and for the guidance of the Contractor."

The first of the definitions says a specification is a "*detailed*" description, the other admits that it is "*more or less*" complete, and rather a guide than definite instructions. If there is already such a vital difference in the interpretation of the word "specification," can we wonder that the opinions as to how a specification should be drawn up in practice are equally conflicting?

A specification must be clear; it should leave no room for doubt as to what is in the mind of the man who issues it, for, unless this is the case, it cannot possibly be clear to the man who is expected to work to it. In many cases the want of clearness in specifications is the first bone of contention. Clearness, however, does not necessitate elaboration of detail. The author holds it to be advantageous to both sides if only such details are inserted as refer to the requirements of the purchaser. Details of construction should, as far as possible, be avoided; they should form part of the tender.

A specification must, of course, include all the following points:

Quantities; performance (with very clear indications as to rating); capacity; emergency requirements; conditions and regulations to be observed to comply with local or other authorities, such as Fire Insurance, Home Office, etc.; time of completion and penalties as far as they are not covered by the "general conditions," guarantees, maintenance, tests, and conditions of same; extras. There will be a number of other points covered by the "General Conditions" which are customarily expressed in a separate document.

The tenderer should be asked to give information upon such specific details of construction and design which may be of interest, as is already done regarding steam consumptions, combined efficiencies, air-gaps, etc. At the same time, the tenderer should be invited to give his reasons for adopting certain practices, to state where, if at all, he had adopted them before, and to supply such photographs or drawings as make it quite clear what is in his mind.

The shorter and more accurate the specification, the easier it should be to determine subsequently whether it has been complied with.

In Germany, France, and America, a specification, as a rule, is identical with standard practice. Unfortunately, in this country we have very few of such standards, and up to recently we had practically none. Even now when certain institutions and organisations have laid themselves out to arrive at more, the authority of these institutions does not seem strong enough to enable them to carry their points. When "standards" have been set up during the last few years they have not been accepted unquestioningly by the profession, and therefore the manufacturers had to be cautious in adopting them.

For instance, the Engineering Standards Committee have settled, amongst other things, a certain standard for the efficiency of carbon filament incandescent lamps, to which the leading manufacturers have agreed to work; this does not prevent some consulting or municipal engineers from issuing specifications entirely different from the standards laid down by the Committee. Consequently a manufacturer cannot be blamed if he uses the recommendations of the Standards Committee only when they are likely to do him no harm.

Specifications drawn up by professional men for the purpose of obtaining tenders should contain a detailed enumeration of articles required, stating where and how they are to be fixed. Each article should be described by an accepted nomenclature which presumes the existence of printed, written, or catalogued detailed description for the benefit of the tenderer. Should these not be accessible, corresponding matter might be added to the specification. Once such a specification is issued no deviation should be permitted unless it is clearly added from the outset that apparatus of similar construction, design, or capacity will be accepted. Goods should not be called for in a specification under a nomenclature which does not denote a specific manufacture or construction, but is a mere indication that a certain dealer supplies them, for that dealer may change the manufacturer but retain his own

trade name for the article. Many such instances are happening through the specifier not always knowing who is a manufacturer and who is a factor only.

The consulting engineer is engaged by his client to define with him his requirements, to specify goods to comply with such requirements, and ultimately to see, when the contract is placed, that its provisions are duly carried out.

We know it is the endeavour of consulting engineers to advise their clients to have the most up-to-date, the most economic, and the best-manufactured plant; but we also know, to our regret, that the number of interpretations of these desiderata is almost equal to the number of consulting engineers in practice, because of the absence of standards, and perhaps because of the absence of some uniformity of education and experience. A closer and more regular intercourse between the manufacturer and consultant would result in benefit to both purchaser and contractor. The majority of manufacturers now gladly throw open their works to consultants at all times, and not merely for hurried visits to their test-rooms. This practice should not be carried to excess as in America and Germany, where frequently the consultant is actually attached to one or the other manufacturing organisation. In this country the status of the consultant is of a different nature, and such intercourse might be practised without any loss of integrity or independence.

Up to now, nearly every specification a manufacturer or contractor receives is different from anything else he has had before, and whilst this may have been necessary in the early days, it seems hardly necessary to-day.

In the early days of electrical manufacturing the professional man had to deal in most instances with small contracting firms struggling for a precarious existence, and apart from technical knowledge a consultant had to display, he also had to be on his guard to see that the way in which various articles were constructed and manufactured was such as to give a reasonable guarantee for their life and efficiency. Also, no doubt, in some cases he had to take precautions to safeguard himself against commercial dishonesty. In a large number of specifications one meets to-day a suggestion of such precautions is still in evidence, and it might, with advantage, disappear from engineering specifications in future. By dishonesty the author means not only the intention of not carrying out a specification as it is meant to be carried out, but also the use of insufficient material, flimsy construction, disregard of proportion, introduction of makeshifts leading to unsightliness, etc.

To-day the weak and incompetent have been weeded out, and there are two kinds of manufacturers left in the running: One class is made up of the large firms who employ the best designers, constructors, and engineers money can procure. The personal element in such organisations is sufficiently strong to combat any attempt at shoddy or incorrect workmanship, and therefore legalisation or specification against

it seems ludicrous. The other kind of manufacturers are the smaller concerns who have specialised in their particular sphere, and they could not have survived if they had not brought brain, character, and the best machinery into play for attaining their positions in their respective spheres.

The author does not say that it is not possible that an apparatus may be turned out which does not answer the purpose, or is incapable of performing its duties, but this can be prevented by an ordinary clear specification without going into details of construction and manufacture. There can be no doubt that, as science progresses, one man, however clever he may be, cannot be expected to know everything—still less to know everything best. Ours is the age of specialising, and it must be admitted that a man engaged in the manufacture and carrying out of certain work must gain knowledge and experience which are denied to those standing outside the executive part of the work. There are consulting engineers who are authorities on one or two, or even more, important subjects, but it is not possible for the professional man to know in every case more and in many cases even as much as those who have devoted the best part of their lives to the practical part of the work.

Would it not be a far happier state of affairs if the consulting engineers, instead of drawing up specifications, each of which is a masterpiece of originality, were to adopt standards where standards are in existence; to accept standard practice where standard practice is established; and to ask the manufacturers in their specifications to put forward their own suggestions? Their work would then consist of going through all the manufacturers' recommendations and suggestions, and to decide which is the best-designed and most serviceable plant, and then to arrive at a decision which is the best for his client to have, taking into account at the same time the various prices.

If such a policy were to become general practice it would encourage manufacturers to establish, where patents, etc., allow it, more standards amongst themselves, and the natural results would be that instead of every article, or every machine, that goes through a shop being different, they would be more alike; manufacturers could produce in larger quantities, which in itself would be a guarantee of better work, deliveries would be quicker, and the cost of production would be reduced, to the ultimate benefit of the consumer and the industry.

In the case of municipal and supply company engineers some of the foregoing remarks also apply, but these engineers have more frequently to be prepared for the acceptance of the lowest tender, without having the same opportunity as the consulting engineer to explain the difference in the offers; and as long as municipalities are governed as they are at present, their engineers will, as far as "detail" is concerned, not be able to alter the present practice very much. It must also be remembered that they are specialists in their particular work, and that in many cases they have more experience of what is actually required than the manufacturer. Especially where large stations are concerned this

experience is valuable, and will help the manufacturer, when expressed in detailed specifications. There should not, however, be such diversity as exists at present in specifications issued by the engineers of smaller stations. Would it be possible through the medium of the existing organisations of municipal engineers to arrive at something like standard practice? It has been done in other countries, and has been done successfully.

There seems to be a fashion in electrical engineering as in most other things, and if one station engineer adopts a new scheme, the principle will in quick succession be adopted by others; nevertheless, the variety of opinions expressed in the specifications is sometimes astounding, and brings for the manufacturing side of our industry unnecessary trouble and expense.

Another reason why the municipal engineer must go into more details in his specifications is the fact that he is governed by Standing Orders, and the specification and tender ultimately form part of the sealed contract.

Where extension work is concerned specifications are often misleading. In some cases elaborate details are given as regards the required performance of the plant, and at the end an insignificant-looking paragraph says that the machine must be identical with the one, or ones, already installed. An actual instance will indicate the dilemma in which the tenderer is often placed: A particular tender specified that the machine would be required to run in parallel with one already owned by the undertaking, and that it must be identical with it. Other conditions imposed in the specification, however, rendered this impossible, and this was pointed out by the author when tendering. His tender was accepted, but he was told that "all the conditions of the specification must be complied with," and he had to refuse the order. The next lowest tender was then accepted, and although it happened to be the tender of the firm who manufactured and supplied the original plant, it took eighteen months to two years for the machine to be accepted, and then, the author believes, only after the contractor had made certain improvements on the machine originally supplied by him, to bring it up to the conditions in the specification.

Another important point which refers chiefly to central station work is the question of cross-tendering between manufacturers of the steam and electrical side, and it has often been suggested that it would be far better if the specifications for combined plant were to be issued separately to the turbine or engine builders, and to the electrical engineers. It is not suggested that two contracts should be given out, but that two separate prices should be received, and that the engine or turbine maker should state that he is prepared to accept the price put forward in his tender from any leading manufacturer of the other part of the combined plant, and that he has included, as is the custom now, for coupling up, combined tests, and everything to make the contract complete. The electrical firms should insert a similar clause into their tender, and should allow extras or

deductions, as the case may be, for the amount of carriage to the works of the leading manufacturers of the steam side of the combined plant. The engineer would then be in a position to choose his own combination, and to find out the exact prices at which he can obtain it, which is not the case at the present moment. Quite recently a move has been made in this direction by a number of leading manufacturers of engines and generators, and it is hoped that the principle adopted by them will be appreciated and supported by the purchasing and specifying engineers.

Another kind of specification with which the municipal engineer is frequently called upon to deal is with regard to installations connected to his mains. There can be no doubt that the corporation engineer has the right to safeguard his interests in this respect, particularly by preventing shoddy and dangerous work being done within the area of his jurisdiction. It is desirable, however, that his rules and regulations should be worded in such a way that they do not leave the contractors or manufacturers at the mercy of his subordinates. It should therefore be agreed upon that, once regulations of this kind are issued, they should be strictly enforced. Goods made by any particular firm should not be specified unless such words as "or other approved type" are added.

Rules for carrying out the actual wiring work are to the benefit of the consumers and are seldom abused. With material, however, things are slightly different. Where it is only a question of construction, the judgment of the assistant under the guidance of the chief can mostly be relied upon. When it comes to the question of "quality," the power vested in the chief's assistant is sometimes far greater than the professional man anticipates.

Rubber may be mentioned as an example. Quite a number of corporations specify that only pure Para rubber must be used in their flexibles, but can any member of this Institution, whether engaged in the rubber trade or not, say that he can in every case decide, after the material has gone through certain mechanical processes, whether the rubber is pure Para? The author recently obtained a delivery of pure Para strip from a leading manufacturer in this country. He submitted it to a leading manufacturer of undoubted repute abroad; and he has now in his possession both a signed guarantee from the supplier that the material is pure Para rubber, and a signed statement from the other manufacturer that it is not.

A certain corporation where the same rule as regards pure Para is in vogue, showed a distinct preference for the manufactures of a certain firm. The author obtained samples from this manufacturer, and asked another leading manufacturer whether he could make pure Para flexible exactly to the sample. The reply received was that he could supply flexible in every respect identical to the sample submitted, but he could not invoice it as pure Para. More for the sake of gaining knowledge than with an eye to business, the author instructed the manufacturer to supply this, and it was invoiced, "Flexible exactly to

sample." The cost was considerably less than that of some which had previously been rejected by the corporation in question, but the flexible was accepted by them as the best pure Para rubber the author had ever submitted.

Another difficulty is the following: An article bearing a certain trademark is found satisfactory and is passed. Subsequently the supplier (who need not be a manufacturer, and very often is not) may have changed his source of supply, and whilst the article has the same trademark as it had previously, on close inspection it will be found that it does not comply with the corporation requirements, but has, nevertheless, been allowed to go on the circuits for years.

Tests are often employed to determine whether an article complies with the specification. Large corporations who have laboratories in charge of a highly trained expert, have no difficulty in making fair and reasonable tests, but it is sad to find what tests are being made in some central stations in order to determine, for instance, the candlepower of incandescent lamps and carbons, and what tests are sometimes applied to determine the life. The specifications for future requirements of such a central station are often based on the results of such inadequate tests, and it is frequently more than a puzzle for the manufacturer to know what to quote for. The most unscrupulous tenderer is always the successful one, and leading manufacturers have found themselves compelled to decline to quote to such specifications.

The next specification for scrutiny is that issued by the adviser or engineer in the employ of commercial undertakings. Orders emanating from such sources are rarely exclusively determined on their merits. Hence specifications are not always binding where details are concerned. It is mostly a question of bargaining, and there are generally wheels within wheels which settle the contracts. One important point in these cases which should not be lost sight of is that the adviser or engineer who issues a specification, although he may not always be an electrical engineer, has no doubt an intimate knowledge of the work the plant called for has to do and the conditions it has to stand, and his specification has to be studied by the tenderer more carefully for that reason.

As he is, presumably, the only man who will have to live with the plant supplied, he must be allowed more latitude in his specification than anybody else. Yet it is just in those cases that the man is most prepared to adopt a manufacturer's standards, and to study existing plants running under the same or similar conditions before definitely settling his own requirements. In some cases only, let us hope, this is accounted for by his limited knowledge of electrical matters. The combination of his thorough knowledge of the work to be done and the conscientious manufacturer's experience, in most cases brings about the complete success of the work, and all he has to do is to choose the right man for it, and to embody into the contract his own ideas about the performance of the plant specified, and all the manufacturer's promises and guarantees contained in the tender.

The specifications drawn up by working electricians, whilst in some cases quite good and workable, in many cases afford great amusement. Such men seldom deal with plant; their specifications are mostly for wiring or small engineering appliances. If they are good ones they are not infrequently taken out of a mauufacturer's catalogue; if they are bad ones they call for well-known, or well-advertised, articles, in many cases irrespective of whether their names indicate the process of manufacture, or simply the name under which they are known in the trade.

In concluding the paper some reference may be made to the subject of contracts. The contract should clearly state whether penalties, or rather liquidated damages, are to be paid in case of non-completion to time on the whole amount of the contract, or only on the non-completed part, particularly in cases where the non-completion does not prevent the purchaser from the useful enjoyment of the other part.

The Arbitration Act of 1889 should be sufficient in the event of disputes, and although the law permits the purchaser's engineer to act as sole arbitrator under certain given conditions, these conditions very rarely prevail, and are difficult to define.

The contract form should be most explicit regarding the much-disputed item of extras, especially in those contracts in which the engineer has power to vary his requirements during the execution of the work. It should also provide a clause as regards any consequences which might arise from the introduction of variation in the work originally called for in the specification, and many a lawsuit can be avoided by exercising care in the formulating of this clause.

In those specifications in which payment can only be obtained under certificate of the engineer, the contract form should specifically stipulate that these certificates cannot be reasonably withheld, and where the time of the last payment is determined by the completion of the successful test on site, or by the time the purchaser has started to work the plant, the contract form should specifically mention that the purchaser has no right to delay the test or the putting to useful work of the plant. It should furthermore provide a definite time for payment in those cases in which delays occur through no fault of either of the contracting parties. The author remembers an instance in which the last payment, which was 25 per cent. of a very substantial contract, was made due one month after the purchaser had moved into the premises. As a fire occurred which totally destroyed the site and its contents just on the day of completion, the contractor never received payment for the remaining part of his contract.

Finally the author suggests the general adoption of the following clause which appeared in the specifications issued by Mr. C. H. Wordingham when he was in consulting practice: "The engineer undertakes that he will consider all drawings submitted by proposing contractors as confidential, and that he will not show any such drawings to other manufacturers, whether they are tendering for this specification or not."

Discussion.

Mr. T. L. Miller: The first criticism I have to make is with regard to the title. The author has entitled his paper "Specifications." I should like to add to that "Specifications—a Plea for the Adoption of Standards of Manufacture." I think the author's paper taken throughout is really a plea for the adoption of standards of manufactures by manufacturers, but I do not know whether he has really considered what that is going to mean. We must not forget that engineering, and particularly electrical engineering, is a progressive science. We are progressing the whole time, and what may be a standard with one firm to-day becomes out of date to-morrow. We can standardise details, and I believe that such standardisation would help manufacturers and the electrical industries very greatly, but I see great difficulties in standardising general design. In dealing with standardisation, the British Engineering Standards Committee have avoided, as far as possible, the standardising of more than details. They have standardised lamp-holders, conduits, and a variety of other things of that nature, but I think it is impossible to attempt to impose one standard of design on all manufactures throughout the country. To do that is to stop progress entirely. Dealing with the title of the author's paper, of course specifications are to be divided into two parts. First the general conditions, which define the relations between the parties to the contract, and then the specification proper, which deals with the details of the work to be carried out. It has been my practice for a good many years now to state in the specification that contractors are to put forward the standard design they have adopted in their own practice. So long as those standards will give the specified results, that is all that is required. To attempt to specify more closely is only to add expense to the completed work. Any one who has been through the shops and has spent any considerable time there knows perfectly well that when we require the manufacturers to alter their standard practice we are leading them and your clients into endless expense, and I think therefore that we ought to be very chary indeed in attempting to specify too closely as to details. As a matter of fact, manufacturers have the remedy very largely in their own hands. I remember some years ago a certain manufacturer who had a special line of motors and his own standard size pulleys; he would quote a definite price for his standard, but if a standard motor and a different size pulley was wanted the buyer would have to pay through the nose for it, and that is where the manufacturer puts the screw on. I am at one with the author with regard to consulting engineers, and all engineers, who are required to specify for machines keeping in close touch with the works. It is impossible for any consulting engineer or any corporation engineer to obtain the latest information with regard to the development of plant unless he is in close touch with the works—for after all, the works have the latest information regarding recent developments. The author refers on page 200 to the fact that "in Germany, France, and America, a specifica- Mr. Miller.

Mr. Miller. tion, as a rule, is identical with standard practice," but my experience has been that where we have to deal with so-called standard practice and where we buy a machine for a certain rated output we probably get our output, but we get very little more; we do not get the margin such as we get with the majority of British manufactures. Then on page 201 the author says, "The consulting engineer is engaged by his client to define with him his requirements, to specify goods to comply with such requirements, and ultimately to see, when the contract is placed, that its provisions are duly carried out." That is so, but I think a consulting engineer's duty is something more than that; his duty is not only to see that his client gets full value for his money, but also that the contractor is fairly dealt with. With regard to the next clause, the author refers to the fact that "we know from our daily experience, that the number of interpretations of these desiderata is almost equal to the number of consulting engineers in practice." Now, if we want to go from the Town Hall to Victoria Station, for example, there are several ways of going there, and they all take us to the station. If one man takes a particular road, it does not follow that the man taking another road is wrong. That there are several ways of reaching this same end is an indication that engineering is progressive science. We are not tied down; we have not got into a groove, and I think the fact that there are so many ways of arriving at the same result is creditable to the profession, and is an incentive to progress.

Then again, referring to standard practices, the author draws a comparison between the practice of electrical engineering and the medical profession. I am afraid his comparison is a somewhat weak one. I dare say some of the members present have had to consult two medical men with regard to some little ailment, but I imagine they have rarely found two medical men treat them in the same way. After all, medicine is an experimental science, and we are the subjects on whom the medical man practices. I was very much struck with the author's remarks again with regard to commercial dishonesty, but really, he should be consistent. He tells us in one place that "during the last twenty-five years commercial honour and integrity has developed to such an extent that he does not think it either right or necessary that specifications should contain anything which was originally meant to prevent dishonesty," and in another place he tells us of the "unscrupulous tenderer" who is always the successful one in tendering to loose specifications for incandescent lamps. Really we have to keep this class in mind. I agree that if we can select the contractor, it is not necessary to put their protective clauses in a specification, but it is our duty to protect our client to the best of our ability, and so long as tenders are publicly advertised, the engineer in preparing the specification must insert these protective clauses. The author, referring to the corporation engineer, speaks about the engineer in the larger station who takes a certain line, and regrets that the smaller men do not follow his example. Further on he tells us that there is a great deal of fashion in electrical work. Now, I am afraid he is pleading in the one case for fashion, and

in the other case is denouncing fashion. With regard to cross tendering between manufacturers, my experience has been that in tendering for coupled generating sets the engine builder sends particulars of his engines to the engineer, and the electrical contractor in sending in his tender refers to the specification received from the engine builder. Of course this reduces very considerably the work involved in sending in alternative combinations. My own practice has been to ask for a considerable number of the more important details of the plant, giving schedules to be filled up by the manufacturers. With such details before him the engineer can very readily adjudicate on the tenders received. By the engine-builder sending in particulars of his plant we reduce the amount of clerical work very considerably, and we reduce the amount of figures we have to go through. Another point to which I would like to refer is a question dealing more particularly with the wiring work where a certain manufacturer's goods are specified. I think that as far as possible we should avoid mentioning the name of any particular firm. If it is done, one method of doing it, and in my opinion the least objectionable one, is to specify a standard of value. I would say, however, "Avoid specifying any particular make." There is one other point, and that is the question of arbitration. I cordially agree with the author in regard to that. I think it is a mistake for a consulting engineer to be made sole arbitrator on his own contract; it frequently gives rise to trouble, and, in my opinion, is unfair both to the contractor and the engineer. Unfortunately, however, this clause is frequently inserted by the legal adviser of local authorities without consulting the engineer. **Mr. Miller.**

Mr. S. L. Pearce: I regard the author's paper as a plea for a duly constituted and recognised Standards' Committee in the first place, from which would follow naturally the more general adoption of standards throughout the country, and thirdly, and mainly perhaps, this paper is a plea for a specification which should be drafted, not in terms of details of construction of the work, but in terms of results to be obtained. With regard to the Standards Committee, we have done a little in this country in that direction, but there is still an enormous amount of work to be done, as anybody will realise from the paper that was read a few months ago by Dr. Pohl.* It is, of course, impossible to standardise all things. Take only two instances. One may refer to the question of standardisation of overload ratings and temperature rises. At the present time the position seems to be pretty well chaotic up and down the country, especially since the introduction of turbo-alternating machinery. These two matters require early consideration, and in connection with the latter the method of measuring temperature rises. We have more or less standardised things such as frequency and voltages, but we have heard the argument advanced that standardisation might lead to the retardation of progress. Mr. Miller has touched upon that, and I do not propose to repeat the arguments. No one, I suppose, imagines for a minute that we could have universal standardisation throughout the country, but I feel we could **Mr. Pearce.**

* *Proceedings of the Institution of Electrical Engineers*, vol. 48, p. 174, 1912.

Mr. Pearce. have more standardisation amongst the individual firms themselves. Pursuing this thought further about the question of standardisation, mention might be made of such matters, for example, as a Standard Specification for Street Lighting. Street lighting is rather a "burning question" at the present time. I am not without hope that before long something in the nature of a standard specification may be evolved as the joint deliberations of all parties interested. I think anything that can be done towards the standardisation of such matters as street lighting will, of course, be an enormous benefit.

Coming down more particularly to the third point of specifications, which the author argues should be defined in "terms of results," he begins his paper with definitions of two well-known authorities. I venture to suggest that the first—Lord Halsbury's—should be taken to imply a specification defined in "Terms of Results," and that Ball's definition bears the interpretation of a specification referring to "Details of Construction." This paper, I have no doubt, is written primarily to concern the electrical engineers, but the author does not make it clear in the case of the consulting engineer whether he is referring specifically to the electrical engineer or the civil engineer. I think we ought to bear in mind that there is a great deal of difference between a specification drafted by a civil engineer and a specification drafted by an electrical or mechanical engineer. It is well known that the civil engineer is responsible not only for the general scheme, but he is also responsible down to the very smallest details, the drawings for which he supplies; the contractor is only responsible for the actual construction. That is not the case with an electrical or mechanical engineer; he lays down the broad lines of the scheme, but he does not design the plant nor the details of the machinery; this should be left to the manufacturer. With regard to the type of specifications, so far we have only heard of two. The first one is the specification which is drafted in detail by the engineer, and the second one is that to which I have already referred, viz., the specification drafted in terms of results that require to obtain. The third specification Mr. Longridge included in his Presidential Address, which is somewhat as follows: "The engineer obtains detailed specifications from various firms, and as a result of careful consideration of these with certain additions of his own he finally draws up a specification." Then we have the fourth specification, which I venture to think will ultimately (having regard to the question of standards being adopted) be the one that will be finally adopted, where the engineer will himself specify the main outlines of the scheme or the works which have to be carried out; he will in greatest detail specify the performance of the plant; he will call from the contractor for the most important details such as the question of efficiencies, overload capacities, temperature rises, and so forth, and the contractor will have to submit with his tender a detailed specification of his standard practices, accompanied with descriptive matter and with complete plans. I think if that is done the manufacturer would be enabled to supply standards, or at any rate, standard

parts, where his ordinary standards would be subject to modifications due to local conditions. Mr. Pearce.

Mr. Miller has touched on the disadvantages attaching to the specification where drafted in great detail by the engineer; it is costly in time and probably costly in money. There is no doubt it leads to a good deal of friction over responsibility, but if we criticise that we must also criticise the specification which is simply drafted in "Terms of Results" alone, because that is undoubtedly vague. It will lead to a good deal of trouble in interpretation, and it is asking one's committee to take a good deal on trust, so that I think the fourth form of specification, which I have indicated, is undoubtedly the most correct to adopt, and one which I venture to hope will be adopted.

Referring to the aspect of this question so far as it concerns municipal engineers, I do not know what inference the author wishes to draw from the fact that this class of engineer is to be prepared for the acceptance of the lowest tender. I admit that there may be difficulties which depend entirely on the capability of the engineer to convince his committee that the lowest tender is not always satisfactory, but apart from that I do not see how we should do as the author seems to suggest, viz., set up one course for the engineer who is not working for a municipality, and another for the municipal engineer. With regard to the question of cross-tendering, I do not think Mr. Miller caught the author's meaning. He seems to infer that all electrical firms do not get a chance. It appears to me to be a matter which must be left to the manufacturers themselves. It is very considerate of the author to take such a sympathetic interest in municipal engineers, but I think most engineers, as a rule, manage to get the combination they want. At the same time, I suggest it is entirely a matter for manufacturers to agree amongst themselves. What we municipal engineers want is to have one man responsible, and it is not for us to dovetail together the various parts of a main contract between the various manufacturers. There is another point to which I take exception, and that is, as I gather from the author's views, that he does not believe an engineer should specify a particular make of plant for any portion of a large contract. I disagree from that entirely. I think if an engineer studies his own conditions and comes to the conclusion that one particular type of plant will best meet his needs, he is quite right to specify, and he fails in his duty if he does not do so. With regard to general conditions, the Incorporated Municipal Electrical Association a few years ago spent about two years trying to draft a set of model conditions, and which were thought to be quite satisfactory to meet the case, but without the support of the Association of Muncipal Corporations it was felt impossible to urge their general adoption. The general conditions which are attached to the ordinary run of specification are as a rule approved and issued by the town clerks of the various municipalities. I hope that this Institution's attempt will bear better fruit than what we tried to do in the Incorporated Municipal Electrical Association. With regard to Mr. Wordingham's clause which appeared in his

Mr. Pearce. specifications, I would only say I should hardly have thought that it was necessary to insert a clause of that description. I think an engineer who had any honour at all would certainly not propose to take any such steps as are indicated by that clause.

Mr. Bevis. Mr. H. Bevis: In connection with this paper the author said a great deal about the establishment of standards. Now the Institution of Electrical Engineers, the various insurance companies, and other technical bodies, have spent an enormous amount of time in trying to arrive at satisfactory standards. Unfortunately it has been found when authorised standards have been fixed, that in a very large number of instances they have been ignored, even by such people as should recognise them. It would appear to me, therefore, that what we want is a standard authority. In America a standard authority is recognised everywhere in that country. Mr. Miller has pointed out the dangers of a standard authority being tied down, and that it would progress. I don't think such would be the case; for any appointed authority would from time to time be able to obtain experience and embody any other requirements, and bring their standards up to date. As some proof of this I would point out that the American and Continental Cable Makers Standards were some few years ago rather low ones, but these have from year to year gradually been brought up to a higher standard. There is no question that the fact of having standards throughout the country would enable manufacturers to work more cheaply and at the same time give consistently better value for the money by the saving of having so many types and patterns. At the present moment it will be found that the requirements of one town with regard to cables calls for one specific quality, and another town quite a different quality, and so on, and although no doubt the various local authorities are desirous of obtaining what is, to their mind, the best results, it can possibly be that different towns require totally distinct qualities. Every one's desire is to acquire the best, and I am sure that every manufacturer would welcome a standard which clearly specified a good quality, in order to put everybody on the same level. The author raises the question of Para rubber. A few years ago when Para rubber was specified, it indicated a standard of high quality rubber; to-day it is somewhat different. It is difficult and dangerous to take it as a standard, owing to the introduction of plantation rubber, a cultivated product of the original wild Hevea. We have yet to learn whether the product of plantation rubber is going to stand as well and be permanently as good as the Para which is gathered in Brazil from the wild trees. The present moment is somewhat difficult, as, in calling for Para rubber, it is exceedingly difficult, after it has been manufactured, to discriminate between the two rubbers, and it is only the cleverest experts in the rubber trade who can tell the difference, and it is next to impossible to prove. Therefore, it would appear to me in view of such being the case, it is wrong to ask for "Para," leaving a loophole for any one with a flexible conscience to supply other grades, and that to-day it would be better to call for a pure rubber cut strip,

as, for electrical purposes, the best strip is undoubtedly a "cut" and not a calendered or spread slightly vulcanised sheet. In conclusion, I would say that in my experience of many years I have invariably found that where a specification is clear and well drawn, and where it is stated specifically what the results required are, it is astonishing how close the tenders are; and what differences there may be are probably only occasioned by the skill, expert knowledge, or other commercial reason. Mr. Bevis.

Mr. A. B. ANDERSON: The author says the man who pays the piper calls the tune, and I am going to say something which I hope will be recognised as being in a broad sense true, when I say that the man who pays the piper is the manufacturer; that we have elected in this country to live very largely by our manufacturing industries, and as I pointed out at the manufacturers' dinner in London, where we had a large number of drawers of specifications as well as users, the man who sells one the dynamo to-day is the man who either himself or through others directly or indirectly dependent upon him, buys the current back from one to-morrow. But I wish to emphasise what I have emphasised before, and what I shall emphasise again whenever I can get an audience to listen to me, and that is that we are all in it together, we are interdependent. It is absolutely necessary for all of us to have good specifications. In so far as a specification is not a good one, it will injure both buyer and the seller. Therefore, there can be no vital controversy within the industry on this question of specifications. Our aim is the same though we may differ as to ways and means, and such discussion as we are having to-night will no doubt largely clear the way towards the specification, which, if I may venture my opinion, should be sane, just, and explicit. But in endeavouring to make them so, we must remember that the English language—according to Murray—is redundant, defective, and inconsistent. It is hardly possible to string ten words together as to which there is no possibility of a diversity of opinion as to the meaning thereof, so that when we have made our specifications sane, just, and explicit, we must also make reasonable allowance for that commercial rectitude to which the author has very properly alluded, which I think has risen in the industries of this country to a very high degree, and in no industry higher than in the electrical industry. I say then, and I repeat, that as business men we know that it is necessary as far as possible to put down our intentions in black and white, but I am satisfied that no specification can be a thoroughly satisfactory one that does not make reasonable allowance for good faith, for which we should allow and which we should endeavour to cultivate, because without good faith neither the electrical industry nor any other industry is likely to reach complete success. Mr. Anderson.

Mr. G. LAYTON: The reason why standardisation has been carried much further in Germany, France, and America than here is, I think, that the great manufacturing firms in those countries are much "closer Mr. Layton.

Mr. Layton. together" than is the case here, and I suggest that "Protection" is the cause of this. The author seems to be looking for perfection in specifications, but this is looking too far ahead. I should feel that real progress had been made if simple standard forms were adopted, and unnecessary "padding" eliminated. We should then know where to look for the vital points, and the manufacturer could readily prepare his tender without the fear of overlooking salient features, which are now too often buried in a mass of words. Specifications are often ambiguous and difficult to interpret, but how much more so is this the case with general conditions, which vary with almost every consulting engineer—sometimes in only a few clauses or even sentences. All of them, however, require a legally trained mind to interpret them rightly, and generally they are very voluminous. It is, therefore, easy to understand the "General" clause referred to by Mr. Pearce, which is usually found in tenders, this clause being of the following nature: "There are a few minor details in your general conditions, which before entering into a binding contract, we should desire to discuss with you." In other words—we have not read your general conditions and have not time to, but shall be glad to do so, if you give us your order. For everybody's sake, cannot buyers and sellers agree to some standard general conditions, and stick to them? We shall then, in course of time, get to know what our obligations under them really are. Reverting to the question of specifications, I think schedules (forming part of the specification, and to be filled in by the tenderer) are one of the finest forms of judging between various offers, but these schedules should not go into too great detail, merely covering the leading features, since manufacturers do not design their machines in detail when tendering; it is, of course, impossible to do so, on account of the time required. Mr. Pearce has suggested the standardisation of temperature rises, overload guarantees, etc. This is a difficult matter since each maker has a line of frames for any particular type of apparatus, which frames necessarily change in size in fairly large steps. For instance, a 100-k.w. machine is wanted; one maker has a frame which will enable him to meet the requirements with a 75° F. rise and a fair overload capacity, while another maker has to go to a much larger frame and could meet the conditions with a 60° F. rise and a very large overload capacity. Naturally it would be better for the purchaser to buy the second maker's plant at a somewhat higher price than the first. It would be better still, perhaps, if the specification was so drawn that the output was not definite, and each maker could offer his nearest frame at its best rating, the temperature rise and overload capacity being limited as suggested by Mr. Pearce. Cross-tendering is undoubtedly a very serious matter at the present day, a great deal of work being absolutely thrown away in this connection. Efforts are undoubtedly being made to reduce this, and there is no doubt the buyer can do a great deal in this direction. It is far too common, even to-day, for a man wanting a steam

generating set to ask the engine builders to tender, each with several makes of generator, and the generator builders to tender with several makes of engines. This is notably the case with advertised tenders. An enormous number of combinations are submitted, involving waste work both to seller and buyer, and the latter gets such a mass of figures that it is difficult, if not impossible, for him correctly to judge the various offers. Mr. Layton

Mr. Thomas. Mr. EUSTACE THOMAS: The impression which this paper has left on my mind is that it is far too general, and it is difficult to get at what the author really has at the back of his mind. The only way to have got any satisfactory criticism leading to constructive suggestions would be to take a large number of specifications, and for the author to draw attention to the points objected to, and to make suggestions for alternatives, which could then be thrashed out. It is easy to understand, however, that such a course might give rise to ill-feeling. The author cries out for more standardisation, and as he is writing of "Specifications," the impression left is that he blames the consulting engineer, or other purchaser. But surely if standardisation is to take place it should start from the manufacturer, since it is he who makes the designs, and if he is a good commercial man he surely tries to keep in constant touch with his market. It is for the manufacturers to get together and standardise designs, having regard to all the conditions of manufacture and to the market, and then to submit their proposals to the consultants or others who issue specifications. If this is done in a sufficiently large way the specifications will soon follow suit. But it is hopeless to expect those who issue specifications to standardise for the manufacturers. Further, standardisation is only possible to a very limited extent, and since so much has been said of the need for it, I should like the author to give a list in detail of exactly what he proposes should be standardised, with suggested standards in each case. The industry is very young yet, and it is constantly changing and developing. Moreover, requirements vary also in a very wide degree. It is particularly interesting that the author's paper, from the manufacturers' point of view, should have appeared so soon after a paper by Mr. Longridge on the same subject from the consulting engineers' point of view. Both have something to say as to the degree of detail desirable in such specifications, and Mr. Longridge gives some illuminating examples of the difficulties that may arise through insufficient detail. The method, however, which seems to best meet all requirements is that the specification should state very clearly the conditions which it is intended to meet, and any conditions as to temperature rise, tests, etc., which may be considered essential. It should also indicate any designs or constructions which the purchaser is not prepared to consider in any case, and might indicate any types of construction specially favoured. This will usually leave many alternatives enabling the makers to put in some standard construction of his, while preventing him from wasting his time on tenders which are hopeless from the first. The manufacturer often has alternatives, and is looking for a lead. This course

Mr. Thomas. leaves the manufacturer free to put in a tender likely to meet with consideration, and also to bring forward anything new and useful. The purchaser also has the advantage of having all new and useful improvements brought to his notice. It is thus left to the manufacturer to describe in sufficient detail what he is offering, and to save expense he will usually have standardised descriptions or illustrations of these, which he may supplement in his letter. It is not fair, however, to call upon all the perhaps numerous tenderers to go with their tender into great detail, or prepare many drawings. It should merely be possible to select from the preliminary tenders those who will have most consideration, and to get them then to enter into greater detail. The customer would ultimately reap the advantage. The contractor, in making out his tender, covers his general expenses, and these are affected by the cost of the many tenders he puts in unsuccessfully. To summarise, if the author wants to do some real good, he should propose a constructive scheme, by which a number of men thoroughly representative of English manufacture—and probably connected by The Institution of Electrical Engineers—would meet to consider in detail a great number of representative specifications, and draft their proposals both as regards such clauses as they object to and as regards standards; they would be met in a friendly spirit by representatives of the consulting engineer, and the matter would be thrashed out on a practical basis. As matters stand, the manufacturers are more to blame than the consultants.

Mr. Frith. Mr. J. Frith: I should like to give a little advice about what is put on the outside sheet of a specification. It is no use putting on the outside that it is a 100-k.w. machine if inside it is stated that it has to stand a 25 per cent. overload for 6 hours, give its output at any voltage from 400 to 550, and run at any speed between 500 and 600. This is a 200-k.w. machine, and it will not be obtained for less by calling it 100 k.w. If it does fall into the hands of a non-technical estimator who quotes a price on the basis of 100 k.w. at 600 revs. per minute, it will do the buyer no good to accept that tender. Is it not also absurd to specify both results and the methods of manufacture to attain such results? Why specify that an armature should be made of Swedish charcoal-iron plates, and be wound with copper wire of 100 per cent. conductivity? If the manufacturer can give us the output, efficiency, and temperature rise specified with a solid brass armature wound with iron wire, why not let him? There are only two conditions which would, I think, excuse the specifying of methods of manufacture; one is to guard against the machine suffering from undue ageing—which cannot by the nature of the case be made the subject of a test—and the second is that the machine is for use in some abnormal conditions, such as a foreign climate, for which certain otherwise standard methods have been found by experience to be unsuitable.

Mr. Cramp. Mr. W. Cramp: There is one point of view which has not been referred to either in the paper or in the discussion to-night, and that is the justification for many of the tiresome details which the author

would prefer to leave out of the specification. I think that these are often due to the sad experience of consulting engineers when dealing with manufacturers, and this sort of experience is by no means confined to dealings with the smaller firms. The great trouble which the purchaser and his engineer have to face is the fact that so few firms have representatives who thoroughly understand the technical side of their work as well as the commercial side. The result is the sort of tender such as I have here to-night. This tender is to a specification for an ordinary wiring contract, and it begins, of course, with the usual covering letter which, however, in this case has printed on its back conditions that contradict directly the general conditions of the specification. Proceeding, it is found that though rubber cable in tubing is called for, 3-core paper-insulated lead-sheathed is offered. One generator which is specified as "direct-coupled to an engine" is offered with a pulley and slide rails. The transformer is specified as "10 k.w." and $7\frac{1}{2}$ k.w. is offered. The following items are put forward by the contractor: (1) Two moving coil voltmeters for two circuits of a 3-phase alternating-current system. (2) Two voltmeter switches 0·50 amperes, 9 in. diameter. (3) One moving coil voltmeter with multi-way switch, 60 amperes. (4) The hand lamps, says the contractor, will each be fitted with 6 yards of wire guard and 6 yards of twin cable. These particulars are sufficient to show the gross ignorance or carelessness of the representative who drew up this tender; but when I say that the order would have been given to this firm on this tender had not a consulting engineer intervened, the necessity for detailed specifications will be seen. Mr. Cramp.

Mr. FRED S. SELLS (*in reply*): In spite of the lenient way the paper has been dealt with in the discussion, I cannot but feel some disappointment that there were not more criticisms and more questions for me to answer, and that I have not succeeded in eliciting from the numerous members who must be interested in the subject a more decided expression of opinion—whether individual or collective—on the various points raised. If some of those who are manufacturers were frightened of offending consulting engineers by a frank exposition of their views, then I can only say that they do not deserve to have their battles fought for them by others. Mr. Sells.

Taking Mr. Miller's remarks first, I may say that I do desire more than the mere standardisation of details up to a certain point; standardisation of design is possible in a large number of directions, and my main contention was that in those cases in which standards are in existence in this country, they are too frequently disregarded in specifications. I am glad that as a consulting engineer Mr. Miller agrees with me as to the undesirability of specifying too closely, and the necessity of consulting engineers keeping in better touch with the manufacturers' works. On one point, however, I must express entire disagreement with Mr. Miller. He suggests that, in wiring work, a "standard of value" may be specified for material required. But if standard of value instead of standard of quality is specified, the whole object

Mr. Sells. of competitive tendering is defeated. Taking the extreme case: If the value or cost of every piece of material in a wiring job is specified, the successful tenderer will be the one who proposes to carry out the work with the lowest price labour and the minimum supervision. Surely the benefit should rather be given to the firm which buys its material from the manufacturer who, by up-to-date methods, improved processes, and automatic machinery, is able to supply the desired quality at the lowest cost.

I perfectly agree with Mr. Pearce's remarks regarding standards. We could benefit the industry at large, if we, in this important manufacturing centre, were to bring greater pressure to bear upon the various institutions to move more rapidly in the matter of establishing standards. Mr. Pearce asked what was the inference I intended should be drawn from my remarks that the municipal engineer must be ready to accept the lowest tender. My point was that this justified the municipal engineer in preparing a more detailed specification than in the case of a consulting engineer, who is in a better position to convince his client that the lowest tender is not necessarily the best. With all due deference to Mr. Pearce, I maintain that, in municipal and non-municipal work, the same course as to detail in specifications need not be followed. The manner in which the tenders are considered by the clients is different, the conditions under which the work has to be carried out are different and, last but not least, the treatment of the plant after it is erected is vastly different. Mr. Pearce is justified in describing the plant he requires down to the minutest detail, but in many private installations the burden of maintenance and repair eventually falls on the manufacturer, and in such cases an open specification enabling the latter to supply standard plant is obviously the more desirable. On the other hand, if the municipal engineer feels bound to carry detail so far that he makes up his mind beforehand that he will select plant of a specific make, I do not blame him for it if he is sure that he wants it; but I do regret that it should then be necessary for him to call for tenders nevertheless.

Hitherto, it has been impossible to get manufacturers to take up collectively the matter of specifications, and Mr. Thomas's suggestion that it is the proper solution is almost a truism. In the meantime Mr. Thomas seems to forget that we have some standards already, but that cases arise daily in which their existence is flagrantly disregarded by consultants. Mr. Thomas and others have made much of the point, with which every one agrees, that complete standardisation from end to end would stop progress; yet apparently he considers that, although some standardisation has been adopted, we must not look to its encouragement or recognition until manufacturers have got together and have standardised designs "having regard to all the conditions of manufacture and to the market." I have quoted Mr. Thomas's own words. His reasoning savours of the academic, and yet he blames me for not having illustrated my paper with a greater number of concrete cases drawn from actual specifications.

Mr. Sells.

I will conclude my remarks by explaining once more that I never intended to detail in my paper all the points which should be contained in a specification; my object was merely to give broad indications of the things which must be included in the average specification and those which should be omitted. There is no doubt that there are cases in which detailed specifications are necessary, and I am the last to suggest that, in such instances, they should not be issued. But, for nine-tenths of the engineering goods required in this industry, a general specification specifying results will be more advantageous to all parties than a detailed specification could be. In the remaining tenth case, in which special circumstances call for special treatment, few manufacturers would object to working to the consultant's requirements; those who felt that the particular details of the specification would place them at a disadvantage could leave the tenders to others whose works and organisation are laid out to deal with specialities. What we must avoid at any cost, however, is the industrial sin of making a speciality of an article which should be the product of standard practice.

NOTES ON POWER STATION WORKING.

By J. W. JACKSON.

(*Paper received 18th January, and read before the* NEWCASTLE LOCAL SECTION *on 11th March,* 1912.)

A few years ago one of our leading consulting engineers startled the electrical portion of the engineering world by stating that the difficulties to be dealt with in the future would be on the mechanical side rather than on the electrical side. In view of the fact that there was a serious amount of difficulty and breakdown on the electrical side at that time, many engineers then considered that a statement of this sort was not at all likely to be confirmed, and yet to-day we find that the mechanical side of a station requires exactly the same close attention that it always did, and that the electrical side of a station very much more nearly takes care of itself. The immediate future should intensify this difference still further when it is remembered that switchboards are being built of the ironclad type, with which it is almost impossible for accidents to the roof or failings of the guarding against vermin, etc., to affect the switchboard. The present-day design of high-class oil switch appears to be not very far from perfection from a general commercial point of view. The protection gear for the cables is also working out in very much the same way. A few years ago a breakdown on a big system would seriously affect a good deal of that system, and very often the whole of it. To-day we find balanced protective relay gear of a very high discriminating value, so much so that when cables break down it is seldom that any other portion of the system is affected than that fed by the particular cable. Even this difficulty is reduced where anything approaching a ring main is in service. Further, because the relay gear has become so discriminating the present-day oil switches are made to operate at such a high rate of speed that the shock to the generating station becomes comparatively small. This point is borne out by the evidence of the breakdown of the cable. Faults on cables are often difficult to locate because the rupture on the broken-down portion is such a small one that it often seals itself up again, whereas in the past there was very little chance of a cable again becoming insulated.

Turning to the mechanical side, we find that the whole profession is making enormous advances, many of which are real advances and others are very old ideas rediscovered.

Turbines.

A very real and solid advance has been made in steam turbo-alternator design and operation, and it seems that here there are distinct possibilities of further improvement.

Design.—Short turbines have many advantages over long ones, some important ones being that they are cheaper to build, safer at fine clearances, they are no less efficient if run at suitable speed, and they can deal with highly superheated steam.

The difficulties of the pure reaction type are due to increased length with size, coupled with fine clearances, both of which are necessary to give the maximum possible efficiency. This makes unwieldy machines above a certain capacity.

Above a certain sized alternator the speed must be reduced, thus calling for a turbine still bigger and longer. The solution of this point has been found in splitting the machines, making two turbines instead of one, one high-pressure and one low-pressure. This is where the "impulse-compounded" and the "impulse-reaction" types come in, because they shorten down the machine to a reasonable length and allow of it being built inside one casing. Many improvements have been carried out on the blading of the purely reaction turbine, and these improvements are still of very high value for future work on the mixed-system turbine. There are still difficulties to be dealt with on the mixed system turbine, such as vibration, but this is only an old difficulty showing itself up again, and can be overcome in much the same way as it was overcome in the reaction type of turbine.

Operation.—Turbines are now built that can be put to work for a whole year at a time dealing with ordinary service conditions without requiring to be opened out, and at the end of that period this is done for inspection purposes only.

When the steam turbine was introduced and the steam consumption was known to be considerably less than for reciprocating engines under similar conditions, the advocates for reciprocating engines found themselves face to face with a very serious rival, and nearly all of them were thrown back on to one common line of defence, namely, the test of time.

There are many large turbines that have now been running for a period of about ten years that were superior in consumption to reciprocating engines and still are. There would therefore appear to be no doubt as to the future of the turbine and for all big power jobs, especially electrical power, air blast, water pumping, etc., the turbine must take its place as the prime mover of the day.

Improvement.—It would appear from present practice that the turbines to meet general commercial purposes most successfully must be of the mixed type—that is, of the reaction and impulse types combined, the favourite design at present being known as the "disc" and "drum." Another satisfactory feature about the mixed type of turbine is that nearly all turbine builders are building it, with very encouraging

results. This means that a tremendous amount of thought is being concentrated on this design.

CONDENSERS.

Several different types of condensers have been put on the market in recent years. These different types have become necessary owing to the demand of the turbine for superior vacuum. It has now been found possible to design a condenser so that the section of its effective body is of the shape of an isosceles triangle (see Fig. 1). One very successful condenser of this type is of the triangular principle, but arranged in the usual circular body (see Fig. 2), so that the triangle is

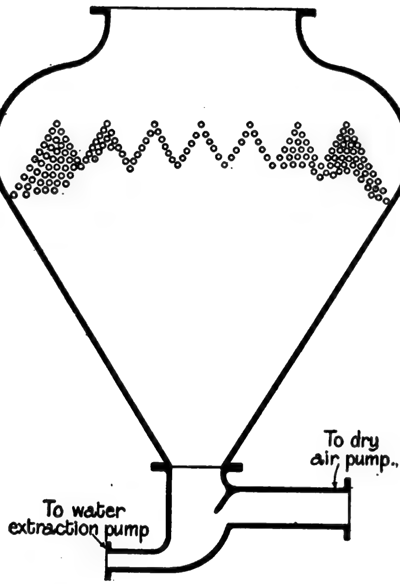

FIG. 1.

cut up into three portions. This may have some slight disadvantage owing to the change in direction of the steam in going from one section to the other, but on the whole it is a very fine compromise. The particular advantage which this condenser offers is that with a first cost very little higher than a simple condenser, it allows of the condensed water being withdrawn at a temperature within a very few degrees of the exhaust steam entering.

Condensers are working showing a difference between these two temperatures of only 3° F., while producing the vacuum of about 1·25 in. to 1 in. mercury of absolute pressure. With the simple type of condenser the same vacuum can be obtained, but the condensed water is

of a temperature from 20 to 30° lower than that of the exhaust steam entering.

PUMPS.

The centrifugal pump in the early days of its development started off against great difficulties, and after many waves in progress, it is more than holding its own. It is now being applied to work that a few years ago would have seemed impossible, and now it seems certain that for nearly all purposes the centrifugal pump will displace the ram pump. We now see the centrifugal pump dealing with large quantities of water at both low heads and high heads, in pumping out dry docks, coal-pits, quarries, water supplies for towns, etc., and there is very little wonder at it taking up this position. The efficiency of the modern centrifugal pump is very high, the maintenance charges

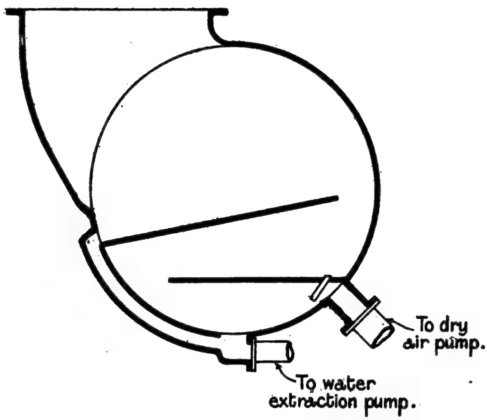

FIG. 2.

are very low, and the reliability is considerable. The main reason for this is that the centrifugal pump takes its water in a manner that is almost entirely free from shock. This action reflects itself throughout the system, as where a centrifugal pump is used little danger is experienced with non-return valves, check valves, starting of pipe joints, cracking of cast-iron pipes, etc., and in the event of a stop valve being shut down by mistake against a centrifugal pump, there is very little danger of the pipes or pump being wrecked, as is the case with a ram pump. The continuous delivery of the centrifugal pump has, of course, some slight disadvantages. With the check valves, a valve lifting for a fixed distance often wears a shoulder on its guide spindles, and so tends to lock itself at that position when a greater quantity of water is passed through. There are very few industries where such a thing as this would be at all serious, and in any case the amount of work to remedy the trouble is very small.

Centrifugal pumps are now being applied to a very much more difficult class of work, namely, that of extracting the condensed water from condensers operating under high vacuum. A very short time ago this would have been considered quite impossible.

The important thing, however, with this pump is, that provided it is built of proper design in the first instance, if the suction side of the pump is kept clear of air, very little difficulty will be experienced. Many pumps in this country have been running for a year and upwards under such conditions.

Still a later development of the centrifugal pump is the rotary air pump. Owing to its special design of impeller and casing, it is able to build up a vacuum and give better all-round results, that is from maintenance and efficiency points of view, than the old-fashioned plunger pump. This rotary type of air pump can be made of generous capacity for its work and yet occupy a very small space. One make of this pump is assisted by a steam jet, the steam jet having the effect of operating in series with the pump. This arrangement proves a very sturdy combination, the steam jet dealing very effectively with an "air" overload in the shape of the leaks which occasionally occur.

From this point of view combination sets of this type have a most promising future before them.

Centrifugal pumps have also for some years been used for pumping the feed water into boilers, and for this work it is very difficult to imagine a better type of pump. The mistake made with some of the very early types of centrifugal pumps was that they were driven at too high a rate of speed—namely, 20,000 to 30,000 revs. per minute. On some makes the turbine is still running at the same high rate of speed, but the pump speed is reduced to 3,000 to 5,000 revs. per minute. This pump speed allows of a fairly robust design.

Boilers.

Alterations have been made in the design of boilers in recent years, but no great increase in economy has been effected. Calculations readily show the reason for this, and do not hold out much hope of further improvement over what has already been obtained. It is true that further proposals have been made to work a boiler with very high speed of gases, by means of which flue temperature is reduced below 212° F., thus utilising the latent heat of the steam contained in the gases.

One of the greatest troubles with boiler operation to-day is just the same as it was fifty years ago, namely, that of admitting just the right quantity of air to the fuel to allow of complete combustion taking place. Tests are recorded as long ago as 1881, on Lancashire boilers using Welsh coal of 14,000 to 15,000 B.T.U. value showing a boiler efficiency of 77 to 80 per cent. and with loco boilers with the same class of coal 80 to 82 per cent. and with various water-tube

boilers 77 to 78 per cent. These figures are, of course, for boilers only; economisers and hot air arrangements were not employed in the tests mentioned. The tests were carried out by such authorities as Professor Unwin, Messrs. Bryan Donkin, Kennedy, Bramwell, Anderson, and some of the water-tube boilers by the British Admiralty. Very few people to-day would attempt to claim much higher efficiencies than these under similar conditions. Improvements have, of course, been made in the way of air seals and baffles, and these undoubtedly reduce the difficulties previously experienced, but a very watchful eye has still to be kept on the whole of the boiler casing, whether of steel or brickwork, the fire-grate, main flues, etc.

Almost all big power stations now employ water-tube boilers only, these for many reasons are used in preference to Lancashire or Marine cylindrical type boilers.

For general all-round work a boiler with straight tubes undoubtedly gives the least trouble, but the boiler with straight tubes that are nearly vertical must surely be the best boiler for all-round purposes. With the best of boiler arrangements and feed-water filters, a considerable amount of mud is found in the boiler water as a result of the completion of the water softening taking place in the boiler. With straight vertical tubes this mud has a chance of slipping into the bottom drum, which should be of fairly large capacity, and so settling to a place where it can be dealt with. Wherever tubes approach anything like the horizontal line, there is always a danger of their being choked with mud at that point where the water is first subjected to the heat treatment which completes the final softening. It is very seldom indeed that trouble from this direction is found on a horizontal tube where that tube is in the front line of steam generation. The circulation set up in this case by ebullition is sufficient to remove all solid matter in the ordinary way, except where the water has been insufficiently softened, in which case a hard scale forms on the tubes.

The other great advantage with a vertical tube is that it does not offer a surface that soot can readily cling to, and this is a very important consideration.

The gas path among the tubes can be so arranged that the gas temperature is reduced to an equally low value with any type of boiler.

This type of boiler calls for a number of drums into which the tubes are expanded directly, and this arrangement has much fewer joints to make and keep tight than most of the various horizontal tube boilers. This makes inspection a comparatively simple job.

A straight-tube boiler has a considerable advantage over a bent-tube boiler of almost any make. For replacement a comparatively small stock of tubes is needed, and further all straight-tube boilers have tubes usually of the same diameter and length, whereas with bent-tube boilers an almost equal number of each type of tube needs to be kept in stock, some boilers having as many as twenty different types of tubes. This is also an important consideration.

Boiler Economisers.

An important advance in boiler work has, however, been made with economisers, and with an economiser of ample size it is now possible to obtain overall boiler and economiser efficiencies of as high a figure as 85 per cent., while still dealing with the boiler in a more or less service condition. Economisers are now so robust that they are looked upon as quite automatic and often left to themselves for more or less long periods. This speaks well for the present-day design, but at the same time close attention to economisers is well repaid in prolonging the life of the metal as well as keeping the economiser casing airtight. By looking after air leaks on a boiler and economiser combined in regular commercial service it is possible to reduce heat losses going up the chimney to about 10 per cent., whereas a neglect of precautions will allow these losses to rise to as much as 30 per cent. and still afford little evidence of what is going on by observation of the colour, which, of course, means the temperature of the flame in the furnace.

The economiser of the future undoubtedly is one built on what might be termed the "Contraflo" principle, where the water is caused to circulate through so many sections of an economiser in series. The water will, of course, enter at the gas outlet end, passing in series through so many groups of sections until it reaches the gas inlet end. Experiments have already been carried out on these lines with beneficial results, showing a higher boiler efficiency than with the economiser arranged as a simple economiser. The cost of an economiser arranged on these lines need not be higher than that of the simple economiser.

Feed-water Softeners.

There are numerous varieties of water-softening plants in practical use, all differing slightly.

Many of these give very satisfactory results, so far as the measuring out of the reagent is concerned. Some types are fitted with exhaust steam heaters. This is, of course, an improvement on the cold process, but the complete softening of the water does not take place until the water has been in the boiler and subjected to the full boiler temperature for some little time.

If sufficient of the reagent has been put into the water, the precipitate becomes mud ; if insufficient of the reagent, scale is, of course, formed. Sometimes the scale is of a very soft and clinging nature, which may cause more serious trouble than where no reagent is used at all. Scale from some waters, even when very thin indeed, gives considerable trouble, while others, perhaps the majority, have been found to form a considerable thickness of scale, without the serious risk which might have been expected.

The frequent blowing down of boilers is a very important matter, and the only safe course to adopt where steam turbines are used is to

have the boiler water analysed quite frequently and the density of solids kept down so low that there is no danger of priming. Almost any boiler on the market will prime badly if the solids are allowed to reach a sufficiently high figure. Dangers from priming with a reciprocating engine are well known, but with a turbine other kinds of trouble follow. One trouble which is well worth mentioning here is that the blades may become choked with mud, usually at a point where the pressure of the steam in the turbine is about atmospheric. When turbines are run with the boilers in a dirty condition for long periods, this matter gradually fills up all available spaces, and its presence cannot but affect the efficiency of the turbine.

No hard and fast rule for the amount of water to be blown down can be stated. Water in some districts is quite soft, and in other districts very hard. The frequency of blowing down will, of course, vary accordingly.

Stoking Gear.

New stoker gear is continually being put on the market with improvements made to meet varying conditions. A great number of the mechanical stokers which are regularly advertised to-day are really first class in their particular line of work. There appears to be very few stokers on the market that will burn any class of coal under varying conditions with equal efficiency. Some coals burn quite readily without furnace arches at all; others require short arches with air admitted between the coal and the arch, and others, again, need specially long arches and will not bear any extra air over the fuel bed. Therefore each coal requires a set of conditions which will be settled by its particular requirements.

It is a very interesting fact that where it is possible to run with a high CO_2 in the furnace, which, of course, means a high temperature in the furnace, the outlet gases will be reduced to an appreciably lower temperature than would be the case if exactly the same amount of load was being dealt with, with a lower CO_2 in the furnace, apart from the question as to whether the leakage through the boiler casing is kept down to a minimum. A reason for this is not at all difficult to imagine. With a fairly high CO_2 the minimum amount of excess air is being passed through the furnace. Therefore, at the load dealt with by the boiler, the minimum amount of total gas is being passed through the gas passages of the boiler, which allows the tubes a comparatively greater length of time in which to extract the heat from the gases. Another interesting feature in connection with this matter is that a smaller amount of power, owing to a reduced water gauge, is absorbed by the induced draught fan when a high CO_2 is being maintained. It is possible to get a CO_2 of 12 per cent. at the exit of the boiler giving a certain amount of gas to be dealt with. If the CO_2 is allowed to fall to about 6 per cent., double the amount has to be dealt with by the fan. This means approximately four times the loss in water gauge in the gas passages of the boiler as compared with the

higher CO_2. Therefore, while it is possible to deal with the gases in the first instance with 1 in. water gauge of draught, in the latter case something like 2 in. water gauge will be required for dealing with the same steam output of the boiler.

In discussing this question of CO_2 obtained on boilers, some engineers claim to be able to work at a very high CO_2, and very few admit that they do work at a lower figure than 10 per cent. It would, however, be very interesting to get information from many engineers as to the position at which the CO_2 is measured and method of sampling the gases. When speaking of the efficiency of the boiler, the only place that the CO_2 can be taken is that of the exit gases, and to have 10 per cent. CO_2 in the exit gases will require on many boilers something approaching 13 per cent. CO_2 in the furnace immediately under the arches. The difference of position at which various engineers sample their gas may perhaps explain a great many otherwise apparently impossible figures. The temperature in the furnace immediately under the firebrick arch, with the CO_2 at that position standing at about 16 per cent., is approximately 3,600° F., the temperature at 12 per cent. CO_2 is about 2,900° F., while at 8 per cent. CO_2 the temperature falls to about 2,000° F. The temperature continues to fall at almost the same rate after that point, as the CO_2 percentage is reduced. From this it will be seen how important it is to keep the boiler and economiser casing free from air leaks, as by keeping the casing tight a comparatively low CO_2 can be run in the furnace and still give a fairly high efficiency. If, however, it is possible to run the temperature up which corresponds to higher CO_2, a very high efficiency can be carried in commercial service. One of the best means for overcoming any difficulty due to low CO_2 in the furnace is that of having two distinct systems of draught—one an induced draught system which will always be able to give a sufficient amount of draught to keep the middle portion of the gas space of the boiler at atmospheric pressure, and the forced draught system which will blow air, preferably heated air, into the furnace at those positions only where it is required. By this means there is no possibility of cold air being drawn into the furnace at places where it cannot be utilised, and if leakages from the furnace do occur, the gas will escape through the boiler casing and show itself up readily, whereas where the boiler is working on a purely induced draught system, very serious leakages may occur, and can only be discovered by means of an analysis of the gases at various portions of the boiler.

Furnace Linings.

Furnace linings have always given a considerable amount of trouble, and it is still a very difficult matter to find the firebrick that will withstand satisfactorily the high temperatures desired for high-efficiency working. Many manufacturers of first-class firebricks will not guarantee that their firebricks will withstand a working temperature

of 3,200° F., and very few bricks indeed will withstand a temperature of 3,500° F.

The Human Element.

After all the latest improvements have been collected together to build up a first-class generating plant, there is still a very important element to be reckoned with, namely, the human element. It will be remembered that earlier in the paper it was pointed out that by varying the CO_2 in the furnace, or, in other words, allowing want of attention, the heat losses going up the chimney may vary between 10 per cent. and 30 per cent. of the total value of the fuel. Allowing a shortage of steam on the turbine neck glands will cause the vacuum on the condenser to drop by quite half an inch. This means about 2½ per cent. increased consumption of steam.

Discussion.

Mr. Gerald Stoney: There are one or two points I would like to refer to on page 221 of the paper. We are told that the disc-and-drum type of turbine is becoming universal. At present this type of turbine is certainly fashionable, and turbine makers, like other people, have to go with the fashion and manufacture the disc-and-drum type of turbine when required by their customers. At the same time I may say that this type of turbine has not been found by us to be cheaper to build, and moreover the consumption is not so good as in the case of a pure reaction turbine. The reason for this is easily seen if we refer to the diagram given in Mr. Baumann's recent paper * in which he gives the curves of efficiencies for turbines with a single moving row of blades and with two rows, the efficiencies under the best conditions being 80 per cent. and 60 per cent. respectively, and I may say that these figures practically agree with ours. If, then, there is at the beginning of the turbine a comparatively inefficient wheel with two or more rows of blades upon it, it seems evident that as good a consumption cannot be obtained as if the whole turbine is of the more efficient type with a single row of moving blades in each stage. There are, however, many other things besides this to be taken into account, and in the case of small high-speed turbines, and also turbines of moderate size where steam pressure is very high and pure reaction blading cannot take full advantage of it, the disc-and-drum type of turbine proves suitable. There is now no difficulty in a pure Parsons turbine in dealing with highly superheated steam, and, further, with the pure reaction turbine there is no danger of cutting of the blades such as sometimes occurs in the case of impulse turbines where there are very high steam velocities. I therefore cannot agree with the author's statement that nearly all turbine builders are building the disc-and-drum turbine with "very encouraging" results. I may say that all our recent large machines are of the tandem reaction type with pure Parsons blading throughout, and Mr. Stoney.

* *Proceedings of the Institution of Electrical Engineers*, vol. 48, p. 768, 1912.

Mr. Stoney. we are now building several of from 6,000 to 20,000 k.w. of this type. With regard to condensers our experience is that a single baffle is as good as three, but opinions vary very much as to the arrangement of baffles in condensers. As regards rotary air-pumps, it seems to me essential that they should not break down if the vacuum falls due to any accidental reason, such as a large air leak. Some types of rotary air-pumps break down under such conditions and cause a lot of trouble before they can get restarted. Farther on, the author speaks of a form of pump assisted by a steam jet. I may say this is merely the Parsons vacuum augmentor, which has been largely used for many years in conjunction with reciprocating air-pumps, and in this instance the only difference is the substitution of a water ejector and jet condenser for the usual reciprocating air-pump and augmentor condenser. The author further speaks about water-tube boilers. Now, it always seems to me that the great fault of this type of boiler is the cost of renewals of brickwork and the large standby losses. In regard to this no boiler can compete with the Lancashire, but of course, the space required for Lancashire boilers in large electric stations is prohibitive. I have often wondered why marine boilers, when they are required on a site to which they could be transported—as is often the case, are not considered. They are universally used in the mercantile marine, and I may mention that in the case of the *Mauretania* the question of water-tube boilers was most carefully considered, and it was decided to put in ordinary Scotch marine boilers in preference.

Mr. Selvey. Mr. W. M. SELVEY: Mr. Stoney touched on the question of what is known as the disc-and-drum machine, with the idea of claiming that this is merely a fashion which has no real economic justification in comparison with the pure reaction type. I think, however, that there is more in it than he says. Mr. Baumann's paper, to which he refers, and which he did not quote quite correctly, gives 67 per cent. efficiency for a two-row Curtis wheel, not 60 per cent., and the odd 7 per cent. makes a considerable difference. A calculation of the leakage of the first two expansions of a Parsons turbine, starting, say, with ¾-in. blades and the usual clearance, will show that there is a good reason for the disc apart from the mechanical and superheat points of view. The fashion Mr. Stoney refers to is not one for disc-and-drum machines but one for small turbines. Power-station machines tend to get bigger every day, and the larger the machines the better, I think, will the pure reaction type come out. Dealing with the question of boilers, Mr. Stoney asks why we do not have Lancashire and marine type boilers, and quotes the boilers of the *Mauretania*. The answer to that is very simple. The *Mauretania* burns coal giving 14,500 B.Th.U. Let them try to burn coal containing 5 to 10 per cent. of moisture, and 15 to 25 per cent. of ash, and they would soon realise the limitations of these boilers with small grates. If in addition to this the load was of the power station order, instead of dead steady, it would be found that the rating of the boiler would be greatly reduced. I would refer those interested to a paper by Mr. Speakman, read before the Institution of

Engineers and Shipbuilders in Scotland on 20th February, 1912. Mr. Stoney has referred slightingly to brickwork in power station boilers, and its absence in marine boilers, but I would mention that I have seen a considerable amount of brickwork in a fine modern marine boiler for a French firm. The real reason for brickwork is that it is practically impossible without it, on a power station load, to get above 6½ per cent. to 7 per cent. CO_2 without black smoke. On the other hand, with reference to Mr. Hunt's claims for high CO_2, I heard of a case quite recently where with a Lancashire boiler, the CO_2 was pushed up to such an extent as to turn the furnace into a coal distillery, so that when the doors were opened to clean the fires, an explosion occurred which blew the flues down. The whole question of renewal of brickwork is that of balancing expense, against the economy resulting from a higher CO_2 and a higher rate of burning on the grate. Up to a certain point it is cheaper to burn the arches down. The same question arises with high superheat: the German experts prefer to push up the steam temperature to 350° C. and over, and to replace the burnt superheater tubes. Mr. Selvey.

Mr. F. O. Hunt: The section on pages 227 and 228, referring to the composition of flue gases, is of special interest to me. It is generally admitted that in the majority of instances the higher the percentage of CO_2 the greater will be economy of working. Although it may be contended that it is possible to bring about wasteful combustion by striving after too high a percentage of CO_2, this reservation can only apply to a small variation at the top end of the range. In any case there is a best percentage for any given plant, and that percentage should usually be a high one, thus pointing to the desirability of some form of indicator to show the percentage attained at any time. The author draws attention to the possibility of error in comparing percentages of CO_2 obtained, and suggests that the errors arise from differences in the positions from which samples are taken. It seems to me that is in itself a very strong argument in favour of a continuous indication of combustion conditions, as it is thereby possible to keep a watchful eye upon air leakage through boiler settings if the sample is taken at the point where the boiler flue joins the main flue leading to the chimney. There are cases where the use of such an instrument has brought to light the possibility of using effectively an inferior fuel to that which would otherwise have been deemed necessary. In conjunction with such a combustion record, a continuous record of the draught at the sampling point, or at the chimney base, seems to me to be capable of yielding valuable information when read alongside of the combustion record. I should therefore be glad to hear the author's views on that point. Mr. Hunt.

Mr. C. S. Vesey Brown: A power station is always working at the critical point, and the anxiety of those in charge is, on this account, just as great at whatever load it is working. The author calls attention to the fact that the mechanical side is of more importance probably than the electrical side. That, I think, has always been recognised. He says that the electrical side takes care of itself, as we know it does when anything happens, but it is taken care of by everybody connected with Mr. Brown.

Mr. Brown. the power station as a rule. I mean to say that the first consideration of most people who have to do with electrical engineering connected with power station work is to look after the electrical side of the system, but the mechanical side should undoubtedly be the first thing to look after. It is obviously necessary to start correctly from the coal pile, for if we have not the right men to put the coal in we naturally cannot get out of the plant as much power as we ought to. Mr. Stoney refers to "fashions" in regard to turbines, and I think he is quite correct. The fashions that have sprung up in power station work are nearly as numerous as those which occur in other phases of life. We can remember when it was the fashion to have nothing but a Willans engine; then came the forced lubrication high-speed type of Belliss and Allen, etc.; then the triple and compound slow-speed marine engine; then the Parsons turbine. From that it became fashionable to have an exhaust turbine stuck on to an old type marine or other style of slow-speed engine. From that the fashion changed to the disc-and-drum turbine, and now the Diesel engine is becoming fashionable, and I can quite sympathise with Mr. Stoney when he calls attention to this. I agree with him regarding condensers. The station is, of course, working at its critical point, and the condenser is even more so. If some accident occurred with the present system of rotary air-pumps, it might possibly cause a serious shut-down, and what we may call a highly scientific method with a certain amount of practice is not exactly the safest or surest thing to depend on. Another point is in regard to water-tube boilers. Water-tube boilers have an advantage in this particular business. Unless we are able to immediately provide for the constantly varying demands which are made on power stations, from fogs or any other cause whatever, which at times demand something from the power station at a moment's notice, and unless we have something out of which we can practically demand the last ounce without any fear of breakdown, we must have very liberally designed apparatus. Boilers do not work at 100 per cent. load factor at any of the power stations in this country, and the only example I know of where a power station and its boilers are worked at practically its full load of 90 to 100 per cent. is at Berlin.

Mr. Jackson. Mr. JACKSON (*in reply*): Mr. Stoney does not entirely agree with me on the question of disc-and-drum turbines. Now, the point I particularly have in mind refers to turbines of what might be termed "ordinary capacity," namely, up to 7,000 k.w. It is very probable that as the capacity is increased after that point the conditions are more favourable to the pure reaction turbine than other types, but up to the load mentioned the disc-and-drum turbine will allow of a much higher station efficiency than the reaction type, the reason of this being that up to now it has been found possible for the impulse stage to carry the highest superheated steam that boilers are capable of supplying under ordinary commercial conditions. The limit of the pure reaction turbine with superheated steam appears to be 530° F. total

temperature, whereas disc-and-drum turbines are running on a total temperature of 800° F. When it is remembered that turbines improve their consumption at the rate of 1 per cent. for each 10° of superheat, or putting it the other way, the total saving to be gained on a station by increasing the superheat 100° F. is 6 per cent., it will not be wondered at that the disc-and-drum turbine is the turbine of the future up to capacities mentioned. The 25,000-k.w. capacity pure reaction turbine, which is now being built by Messrs. Parsons, and referred to by Mr. Stoney, for the time being must remain a law unto itself. The low-pressure end of any small turbine should undoubtedly be of the reaction type to obtain the highest possible efficiency. **Mr. Jackson.**

Regarding the question of condensers, the special advantage of the condenser which is spoken of in Fig. 2 is that it allows of the highest thermal efficiency with regard to the drop of temperature between the exhaust steam and air-pump discharge water. The particular point to observe under this heading is that condensers are working with temperature differences over these two positions of only 2° F., but still giving as high a vacuum as it is possible to get with any similar air-pump, and undoubtedly it is not possible to obtain such a low temperature drop with any other design of condenser.

With regard to Mr. Stoney's remarks on rotary air-pumps, I have had experience with a rotary air-pump that is used in conjunction with a steam jet, known as the "kinetic" pump, which deals with a very serious air-leak into the condenser system, and appears to be no more likely to sit down to such an air overload than any type of reciprocating air-pump, but under ordinary commercial conditions it will pull down to better than 99 per cent. of the theoretical vacuum corresponding to the temperature of the vapour and water entering the pump. In addition to this the condensed steam is returned to the hot well 5° to 10° F. hotter than the temperature of exhaust steam entering the condenser, this temperature depending upon the amount of steam used in the jet. On the other hand, certain other rotary air-pumps have been put on the market, and do sit down under a heavy air load in the manner pointed out by Mr. Stoney.

With regard to Mr. Stoney's remarks on boilers, I am surprised to hear that the old marine type of boiler is superior to the modern water-tube boiler. It is quite true that one boiler is more suitable for one class of work than another, but in power station working the water-tube boiler is undoubtedly a necessity, and it also seems to me that the water-tube boiler can be fitted with advantage in the place of almost all cylindrical boilers, among the reasons being that it can handle superheated steam so easily that it responds to emergencies very quickly, and it is very free from circulating troubles which the cylindrical boiler is heir to. Another serious point against the ordinary marine boiler is that of smoke. With ordinary water-tube boilers, which permit of large furnaces lined with refractory lining, it is possible to work at very high CO_2 smokelessly when using any class of bituminous coal. This cannot

Mr. Jackson. be said about the cylindrical boiler. One or the other of the two desirable points, namely, economy or smokelessness, has to be sacrificed with this boiler. A further point against the cylindrical boiler is its weight per unit of work. I have often thought that had the *Mauretania* being fitted with water-tube boilers, which weighed no more than the cylindrical boilers that she is at present fitted with, she would have done a higher sea speed without consuming any more coal. The question of boiler brickwork was also touched upon. The total cost per annum for this, however, is very small compared with the total gains made in efficiency of combustion with refractory linings; £10 worth of bricks make a very big show, and also, as Mr. Stoney says, "occasionally a big mess."

I quite agree with Mr. Hunt that CO_2 recording machines have a most important function to fulfil. Unfortunately they are not always kept up to the state of efficiency which they demand, and hence frequently earn for themselves a bad reputation, but money spent in this direction is money well spent, as a really effective check can be obtained in this manner on the combustion and general attention to the furnaces over any period, and this is almost the only way of getting the information that is required at reasonable cost. I agree also that electrical gear requires some attention, but I started off by assuming that it would get it. My point was that the small amount of attention necessary has been thoroughly well worked out; but no matter how much attention the mechanical side gets, trouble is still met with.

HIGH-TENSION PORCELAIN LINE INSULATORS.

By J. LUSTGARTEN, M.Sc., Associate Member.

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SUMMARY OF CONTENTS.

ELECTRICAL PORCELAIN.

General Remarks.—Electrical porcelain is eminently suitable for permanent exposed insulation, for which it best fulfils the necessary requirements. It is not hygroscopic nor inflammable, and does not alter in composition with time; it is unaffected by atmospheric action, and by practically all chemical substances. Under electrical stress its resistance to puncture is high, and even with prolonged application it undergoes only a slight rise in temperature, which is of little consequence. The material has one bad characteristic—it is brittle. This, and the difficulty of manufacturing very intricate pieces, militate against its universal adoption in the electrical industry. Still, by proper design the objections caused by brittleness can to a large extent be overcome.

The essential components of the insulator "body" are kaolin (china clay), some form of silica (such as quartz or flint), and felspar. The mixture is raised to the vitrifying temperature, causing chemical interaction between the silica and silicates, which ultimately produces a homogeneous mass. Ordinary felspar is potassium aluminum silicate. Pure kaolin is hydrated aluminium silicate produced by decomposition of felspar under the action of weather, but even in the best natural state it is contaminated with undecomposed felspar, grains of quartz, mica, etc. Quartz and flint are practically silica.

The different character of the various ingredients used in making the insulators in England, Germany, and America necessitates a difference in the process of manufacture. In England the body is made up of kaolin, plastic or ball clay, flint, Cornish stone, and felspar. The ball clay, which is in a preponderating amount, gives plasticity, makes the mixture easier to work, and renders the finished insulator less liable to mechanical damage—*i.e.*, less brittle. The Cornish stone is a fusible natural rock consisting mainly of felspar and quartz. On the Continent the mixtures generally contain only kaolin, felspar, and quartz, and the resulting porcelain is whiter, though this is not so much due to the composition as to the method of firing, while the electric strength is probably greater.

Manufacture.—After calcination and preliminary crushing, the flint, felspar, and other rocky ingredients are water-ground until they are fine enough to pass through silk lawns 100 strands to the inch. The clays are beaten up with water in a large iron churn or "blunger" to a creamy fluid, known technically as "slip." All the ingredients are then mixed in proper proportions in the presence of water, to obtain the intimate mixture necessary for proper manufacture. The milky fluid or slip is passed through sieves of brass wire, phosphor bronze, etc., and then through a trough containing a row of magnets to arrest iron particles, after which it is pumped into a filter press under a pressure of about 4½ atmospheres. Some manufacturers then store the resulting sheets in cool, damp cellars. The next process is to knead the sheets in a pug mill, which solidifies the mass and drives out any enclosed air-bubbles. The clay is cut into slices, which are thrown heavily one upon the other on a "wedging" slab. The several processes described are for the purpose of rendering the mass perfectly plastic and homogeneous.

In English practice the first operation in the manufacture of the insulator is to manipulate on the potter's wheel a clay ball of proper weight to the shape either of a dish or a solid cylinder. After this the work passes to the first drying-room, which is kept at a temperature of 80° F., to expel a portion of the moisture. The turner thus receives the pieces at such a consistency that they can be placed in a cup chuck or on a "dicing" lathe. The bolt-hole is then tapped in the interior of the solid pin insulator, or the lowest shed of a multi-piece insulator. The insulator or its component parts go to a second drying-room to be slowly and perfectly dried before going to the kiln to be fired. They

undergo scrutiny by "fettlers"; the slightest sign of flaw condemns the piece. At this stage they are as strong as blackboard chalk. The articles are placed in coarse fire-clay boxes or saggars, which are stacked concentrically in a vertical reverberatory furnace; the doorway is walled up and heating commenced—at first gently to expel the remaining moisture, then at a dull red heat to drive off the water of constitution of the clay, and the material is then raised to a vitrifying temperature of 1,250° C. to 1,300° C., depending on the composition of the mass. This "bisque fire" occupies from two to three or four days, when the kiln is allowed to cool for a similar period. The "biscuit" insulator, which has shrunk about 16 per cent., linearly, is examined before glazing. In this biscuit state the insulator, though hard and of good electric strength, has a surface which attracts moisture, though without sensibly absorbing it; this surface would gather dirt and soot, and owing to the superficial irregularities would be very difficult to clean. For this reason, and no other, a coating of smooth and durable glaze is used. The ingredients of this glaze are kaolin, borax, felspar, whiting, and lead monoxide, which, being readily fusible, produces the glassy surface. The glaze may contain different metallic oxides to give either a yellow, brown, green, blue, or black colour. A brown colour can also be obtained by using a red marl in the clay body, such as is employed on vessels for mast shackle insulators (see Fig. 23). These oxides are non-conducting and therefore do not affect the insulating properties of the porcelain. The coloured glazes have the disadvantage of being more fusible than the white, and therefore exhibit uneven depth of colour, especially at the edges. Muffled kilns for coloured glazes appear to produce better results. Parts intended to be cemented to metal are left unglazed by wiping the glaze off with a sponge before firing. The glazing or glost oven is fired to a lower temperature than the first oven.

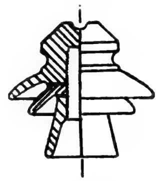

FIG. 1.—Solid Insulator of three Sections before Firing.

In German practice there is a difference in the methods following the wedging stage. The clay is put into a plaster of Paris mould of two halves of the shape of the finished part required, but about 20 per cent. larger. The clay is pressed together and the mould is allowed to stand until the clay has shrunk somewhat owing to moisture being absorbed by the plaster. The mould is opened and the shell allowed to dry without employing heat preparatory to burning in the first oven. The shells taken from the mould can be stuck together by the help of fluid clay or "slip," if intended to form a solid mass, otherwise the shells are cemented together after the final firing. Fig. 1 shows an insulator made up of three sections stuck together, the neck and bolt-hole being cut after the drying stage. The first oven is at a temperature of only 800° to 900° C., which serves mainly to expel the water of constitution from the clay, but leaves an unvitrified substance which is only about as hard as a clay tobacco-pipe, the surface being

rough and porous to water, the porcelain is then dipped into the glaze, which in this case consists only of felspathic materials and quartz, and is subjected to a second firing at a higher temperature, about 1,400° to 1,500° C., which finally vitrifies the body and matures the glaze at one operation. Of the coloured glazes, brown and green seem to be most favoured, as they are the only ones that can be successfully produced under these manufacturing conditions.

The American method is very similar to the German. The conventional design of American insulators is by nesting thinner and more shells together than in the European design. Each shell is made from a mould, which is placed on a potter's wheel and the clay on the top

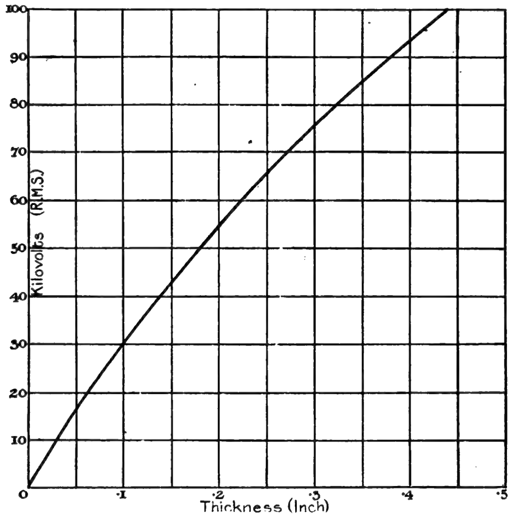

FIG. 2.—Curve of Puncture Voltage and Thickness of Porcelain.

shaped by a forming tool called a "jigger." Suspension types are also made in this way. The shell after being taken out of the mould is allowed to dry for about two weeks. The thread for the bolt-hole is cut out, or the holes for the interlink types are made (see Fig. 26), which for the latter is a difficult operation. The insulator is then dipped into a glaze and fired to vitrifying temperature.

General Properties.—The shrinkage of the porcelain insulator depends upon whether it is turned or moulded, and also upon the composition, size, and thickness. From the stage before the bisque-firing to the finished stage it is 13 to 17 per cent. for lathe-turned, and for moulded insulator parts slightly less.

The density of porcelain is about 2·3 to 2·4. English electric porcelains will not absorb water whether glazed or unglazed. To detect absorption dip a broken piece of the insulator into water

coloured with anilin or fuchsin. No colouration should be maintained at the break. Bad porcelain can be detected by its adhering to the tongue.

The linear expansion coefficient of hard porcelain is between 0·0000045 and 0·0000065 (C.), being less than that of glass. This is a recommendation, as the porcelain will withstand changes of temperature better. The more felspar in it, the greater the linear coefficient; flint has the opposite effect. The relative heat conductivity to that of silver (taken as 100 per cent.) is 0·045 per cent. Its specific heat is 0·17.

Electrical Properties.—The specific resistance can scarcely be given as a property of the material, but rather as the property of the surface conditions existing on the test-piece. The surface leakage is more important than the actual leakage through the material, and the former has nothing to do with the material itself, but depends upon the humidity of the air and other circumstances affecting the surface. With clean glazed porcelain at normal temperature and humidity the specific resistance on a test-piece amounted to 2×10^{12} megohms. As with all silicates, porcelain becomes conducting when raised to a red heat.

The dielectric constant obtained with direct current is about 5·3. With alternating current the value for a frequency of 50 is about 10 per cent. less, diminishing a further 3 per cent. for a frequency of 100.

The electric strength of porcelain will depend on the manner in which the clay has been worked and the disposition of the thick parts. The requirement for a high electric strength is a thoroughly homogeneous and vitrified mass, which, however, is difficult to attain with increasing thickness. The curve of puncture voltages for various thicknesses of porcelain plates tested between a sphere and a plate is shown in Fig. 2. In the English method of manufacture the glaze does not add to the electric strength, but in the German method the full strength is not attained till after the glazing, when the whole mass is fully vitrified. Should the glaze be of poor material it will in time become influenced by weather conditions. To obtain the necessary thickness for resisting puncture and to provide for a factor of safety, two or more shells are cemented together, the insulator thus obtaining a more thorough vitrification.

Mechanical Properties.—The greatest mechanical strength of porcelain is in compression, being about 30 tons per square inch, only 30 per cent. less than cast iron. The exact tensile strength is difficult to obtain, owing to the small distortion of the test rod during firing, which subjects it also to a bending stress. From a large number of results the mean is about 10 tons per square inch. The tensile strength of porcelain from experiments on bending is about 3 tons per square inch. The shearing stress of good cement is about 1,600 lbs. per square inch.

Porcelain is harder than the rocks from which it originates. Its surface can be penetrated by a diamond point only under great load; the hardness of the vitrified Continental porcelain being about 5 to

10 per cent. greater than the outside glaze. This hardness gives the surface its weather-resisting property and its permanency; even the brush and spark discharges do not affect its insulating power.

LINE INSULATORS.

General Remarks.—An insulator has to satisfy two main conditions. First, it must withstand the mechanical stresses necessary to support the conductor, and, secondly, it must withstand the electrical stresses necessary to insulate it. Additional requirements are: (1) It should be able to resist atmospheric influences in service; (2) it should not be easily broken by stone-throwing, bullets, etc., nor in transport; and (3) its weight and cost should be as low as possible. The properties to be held in view are therefore great mechanical strength, high electric strength, small conductivity, small surface leakage, a size and shape to exclude electric discharges, and to fulfil the three other requirements mentioned above.

The long spans which have come into use subject the insulator to very great stresses. These stresses are due to the following causes: (1) The weight of the wire coated with snow and ice (especially with aluminium conductors, which require a large diameter); (2) wind pressure and extreme cold; and (3) the horizontal pull of the wire. The latter stress is the most important, especially when the wire breaks. The stresses are exceptionally great at corners and dead-ends.

The insulator withstands a compression test best; hence in the pin type the pin is threaded up into the head of the insulator, so that the porcelain is only in compression but not in shear. The insulator can be designed to withstand such heavy testing loads as 3 to 4 tons, the pin bending before fracture of the porcelain commences. The suspension cemented type (see page 260) can be designed to withstand a continued shear and tension up to 5 tons. In practice, conditions are arranged so that the wire will break or the pin will bend before the porcelain gives way.

The shutdown of a line owing to a punctured insulator, the waste of time locating it, especially when covered with snow in high mountainous regions, and the actual loss of the insulator have called attention to the necessity for a high electric strength, and a design in which the insulator must rather flash-over than puncture. A safeguard against the porcelain fracturing in case of flashing over is discussed later. With small insulators the safety against puncture and flash-over is so high that the more important consideration is that of mechanical strength.

The conductivity of porcelain is so low that leakage through the material needs no special consideration in design.

The surface resistance must be sufficiently high to prevent neighbouring lines (especially telegraph and telephone) being influenced by the leakage current. In general, the insulator will have a high surface resistance if ample provision has been made against

electric discharges on the insulator under adverse climatic conditions.

The provision against discharge will be best considered in the brief description of the development of the modern pin insulator.

Pin Insulators.

Development.—The prototype of the modern high-tension insulator was a petticoated insulator of the same cylindrical form as the low-voltage telegraph insulator, but somewhat larger. With a line pressure of only a few thousand volts the necessity for providing a safety factor against brush discharges and sparking over was unknown. Surface insulation was considered the most important point, and the insulator was designed accordingly. To increase the surface resistance a triple-petticoated insulator of the same form was tried, but as the narrow spaces soon became filled with insects, etc., a reversion to the original type was made. On raising the pressure the narrow spaces became filled with a glow and brush discharge, these constituting a loss. Under rain this takes place earlier, and a brush discharge starts from the wet edge of the outer petticoat to the bolt; the spark which follows bridges the flanges. The action is assisted by drops of water from the outer petticoat, being pulled inwards by the strong field. In high-tension insulators the surface resistance is of subsidiary importance. The following experiment will show that sparking between two electrodes on a surface does not depend upon the surface resistance (except when moisture is deposited). Fig. 3 shows a porcelain plate, on the centre of which is a disc electrode and at the edge a tin-foil electrode. A metal rod touches the latter and can be inclined at various angles θ to the plate. For a constant sparking distance d of 6 in. the value of the spark voltages for various inclinations of the rod are given in Table I.

Table I.

Angle of Inclination. θ	Spark Voltage. Kilovolts.
0	35·4
15	46·4
30	50·5
45	55·5
60	59·0
90	60·0

Here we have the surface resistance constant, but the spark voltage varies on account of the altered flux density at the centre electrode.

The next development was to incline the petticoats outwards in the form of a cone, thus moving the outer wet flange farther from the bolt whilst still keeping the inside surface dry. An increase in the

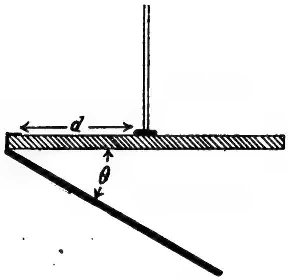

FIG. 3.—To illustrate the Effect of Flux Density on Sparking Voltage.

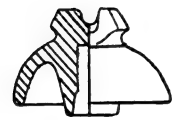

FIG. 4.—Early Locke Insulator.

dimensions also made this insulator comparatively heavy. Investigations at this time showed that the drops of water (which influence the brush discharge and flash-over) could be driven outwards by spreading the outer shed, giving it an umbrella shape; the weight was thus reduced. (Fig. 4 shows an early American type.)

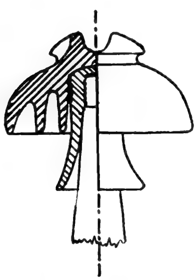

FIG. 5.—Early American Two-piece Insulator with Wooden Pin.

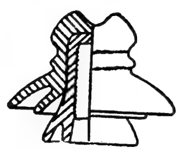

FIG. 6.—Hermsdorf Delta Two-piece Insulator (1897)

With the use of higher pressures the solid insulator frequently punctured during test. In the attempt to obtain large sparking distances, the required thickness to prevent puncture was too great to be without flaws. The next development was an insulator made of two pieces cemented together. Fig. 5 shows an American type, and Fig. 6 a delta insulator produced about 1897. The wooden pin was early recognised as delaying the production of brush discharge. About this

time the Paderno insulator of Ginori was introduced. The type is similar to that of Fig. 7 A, and virtually consists of two similar insulators of the early form one above the other. The type* has been largely retained with but slight modifications in the head-piece and the pin-piece. Lengthening the pin shed and extending the outer shed horizontally to increase the striking distance resulted in the insulator shown in Fig. 8 (Bay Counties, 1900). This insulator endeavours to combine the alternative ways by which insulation of two electrodes for

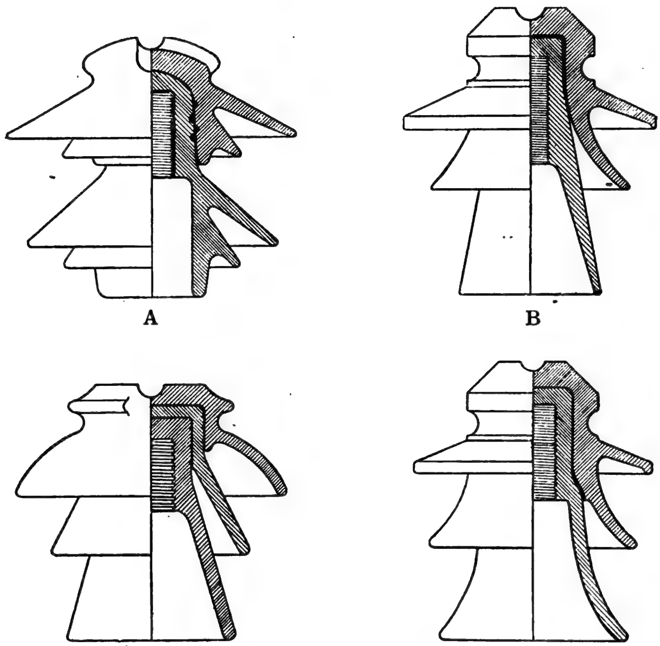

Fig. 7.—Pin Types for Line Pressures of 35 k.v.

A. Italian (Ginori). B. English (Bullers).
C. American (Locke). D. German (Hermsdorf).

a given spark distance can be effected. The pin-piece alone would be no better than the above telegraph insulator, and the head-piece alone would be equally ineffective. The combination of the two still has a considerable wet surface leading to brush discharges, as Nature does not confine herself to vertical downpour but also furnishes driving rain. It is useful for places near the sea, where salt deposits accumulating on the insulator act as a conducting surface—the cleansing action of rain is therefore a necessity.

* The more recent "Normale" type for higher pressures is constructed on the American pattern.

To minimise the wetting of the lower surface the intermediate petticoat or shed was retained. The first European 40-k.v. line (Gromo-Nembro, 1903) was equipped with the insulator similar to that shown in Fig. 1. This shape has been largely retained for pressures up to 40 k.v. (Fig. 7 B). In America the multi-shed insulator (Fig. 7 C) was quickly developed for higher pressures. Fig. 9 shows

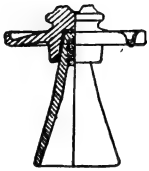

FIG. 8.—American Bay Counties Insulator (1900).

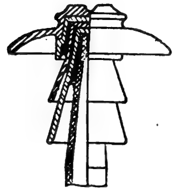

FIG. 9.—Guanojuato Insulator, Locke (1904).

the Locke insulator for the Guanojuato transmission line (1904), and Fig. 17 an insulator with long shells designed by Mershon for the Niagara, Lockport, and Ontario 60-k.v. line. Fig. 7 D is the Hermsdorf 1908 type with a greater curved pin-piece and reduced length of bolt-hole. A similar 3-piece insulator is used on the 66-k.v. European line, Molinar-Madrid (1909).

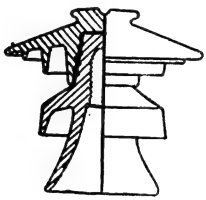

FIG. 10.—Rosenthal Insulator.

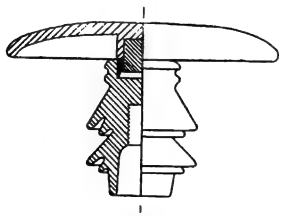

FIG. 11.—Semenza Insulator with Earthenware Cover (Ginori).

The intermediate shed takes various forms. It may assume that of a projection on the pin-piece itself, as in the Rosenthal insulator (Fig. 10), which also shows a petticoated head-piece.

The Semenza (Italian) insulator (Fig. 11) has an exactly opposite function to the insulator of Fig. 8. The intention is to preserve a dry state of the surface. It is protected by a porcelain cover of a cheaper kind of porcelain, screwed or cemented to the insulator proper. Its wet flash-over voltage is thus considerably increased, thus enabling a smaller size of insulator to be used for a given line pressure. The metal-covered insulators discussed on page 252 serve the same purpose, from many points of view, in a better manner.

Electrical Considerations in Design.—Improvements in the process of manufacture have made it possible to produce a thickness of shell

of $\frac{3}{4}$ in. to withstand 100 k.v.;* above this small cracks or flaws in the interior are likely to occur. The practice in this country and America is to make 2-piece insulators for line pressures from 10 to 30 k.v., and 3-piece from 30 to 50 k.v.; above this in America 4-piece insulators are made up to 70 k.v.; but suspension insulators are rapidly superseding the pin type from 60 k.v. On the Continent the single-piece insulator is general up to 20 k.v., and the 2-piece to 60 k.v.

The necessity for providing large air-spaces is seen from the results in the Appendix. Consider the flux passing from the line wire and the tie wires at the neck of the insulator to the bolt. At the top of the bolt the flux passes wholly through porcelain; but further from the bolt it must pass partly through air. The flux density will depend upon the thicknesses of porcelain and air encountered in the path of the flux. At the neck the distance between the electrodes being a minimum, the flux density is greatest. The starting of a glow at the neck depends on this value, which can be reduced by increasing the thickness of porcelain. For other flux-paths the density is smaller; and when these paths traverse air and porcelain, this flux density will be smaller the smaller the thickness of porcelain encountered—*i.e.*, the greater the length of air-path. The insulator with large masses of porcelain and narrow air-spaces will not only require a greater charging current, but will also have a tendency to glow in the air-pockets.

As the pin shell has the smallest diameter at the neck of the insulator, the flux penetrating will produce a greater potential gradient than the others. Thus it will have a greater tendency to puncture, as is shown by the following results: Out of 10,480 3-piece insulators tested to a dry flash-over voltage of 195 k.v. for 3 minutes, 4,172 failed, of which 2,317 failed in the pin shell, namely, about 55·5 per cent. Of the failures, 81·6 involved the pin shell.†

Taking the flux-path in air constituting the spark distance for the insulator in the dry state (Fig. 24), the flux density is still somewhat influenced by the porcelain flanges. The following experiment (Table II.) shows the influence of a medium of greater dielectric constant on the flux density of a spark-gap. A sheet of porcelain was gradually brought up between two pointed electrodes separated 3·32 cm. apart, and the spark voltage was observed for different positions of the plate.

(The reduction was more marked with plate electrodes. For the same distance apart the flash-over voltage was reduced from 36 to 31·8 k.v.)

The necessity for a large cylindrical air-space between the bolt and the lowest shed is evident from the conclusions in the Appendix. The nearer the porcelain is to the bolt—viz., the electrode—the greater is the total flux. A narrow air-space may lead to brush discharges within, especially when the lowest shed is wet. Curving the lowest shed outwards, a greater striking distance between it and the bolt is provided.

* Under oil, a plate of this thickness punctures at about 105–110 k.v.

† *Transactions of the American Institute of Electrical Engineers*, vol. 29, part 1, p. 590, 1910.

Curved sheds have, on the whole, greater advantages than straight. Rain falling at 45° can be deflected away from straight sheds, but with curved sheds there is a splashing action, with a consequent slight wetting of under surfaces. With the straight-shed insulator insects and dust may lodge where driving rain cannot reach, but this is not the case with the curved.

A slight conical formation of the head-piece helps to keep the under surfaces dry. With the head-piece wet, the total flux is increased, For paths near the flange the flux density will be considerably increased, owing to the point action of the drops of water. If the under surface of the head-piece and the upper surface of the intermediate become wet, then the distance between the electrodes is considerably reduced. In the air-spaces between the intermediate and the pinshed and between the latter and the pin, the flux density may produce discharges. The shells concerned are subjected to greater stress. Finally, when all surfaces are wet except the inner of the bottom shed, the latter will undergo maximum stress. The flux density from this flange

TABLE II.

	Height of Porcelain from Line joining Electrodes.	Flash-over Voltage.
	Centimetres.	Kilovolts.
Points above porcelain edge	4·0	21·8
	3·2	21·5
	1·3	21·1
	0·4	20·7
	0·0	20·1
Edge above points ...	0·4	21·7

to the bolt will be greatly increased. Both leakage and displacement (charging) currents will become great, resulting in great loss (see page 272). The latter is an exceptional condition which might only occur with thawing snow or hoar-frost deposited between the shells.

Long insulator parts, as in Fig. 17, have a large capacity—viz., produce a large total flux—since porcelain replaces air in the long flux-paths. In these long paths the flux tends to seek stronger fields, and thus a crowding takes place, putting greater stress on the parts, especially the pin-piece. Experience shows that long insulator parts do not resist sudden stresses well.* Shorter insulators give a better distribution of the flux, and enable the bolt to be shorter, thus securing additional mechanical strength. Large diameters give increased capacity. Wide and high insulators both give increased electric charge, and flash-over takes place by surface sparks (see page 276).

* Nicholson, "Protection of Insulators from Lightning Effects," *Transactions of the American Institute of Electrical Engineers*, vol. 29, part 1, p 573 (1910).

Forms of Electric Discharge.

(*a*) *In the Dry State.*—The two forms of electric discharge—the brush and surface spark—are responsible for the flash-over of an insulator in the dry state, the brush predominating in the case of small pin insulators, the surface spark for very large insulators (Fig. 12), and a combination of the two forms for medium-sized insulators.

As the pressure on the insulator is gradually increased a glow appears at the neck and extends to a surface brush down the shed, as in Fig. 13. The glow may also commence within the pin shed and at joints if the flux densities are high and are sufficient to produce the requisite ionisation.* With increase of pressure on the top shed streamers or surface sparks will form. The requisite pressure is dependent upon the thickness of porcelain, length, and disposition of the sheds. Meanwhile brush discharges start from the bolt and the line wire, commencing earlier from the wire if placed in the side instead of the top groove of the neck. On small insulators these brush discharges produce the pilot spark, which may reach to the neck *viâ* the surface brush or direct to the line wire, as in Fig. 13, according to the potential gradient acting along these respective paths. Thus for small insulators neglecting the reduction produced by the porcelain flanges, the curve for spark voltage and spark distance will be of the same order as the spark voltage distance curve for the line wire and bolt with surfaces at right angles. With medium-sized insulators the surface sparks commence on the top shed and the pin shed; a brush discharge completes the flash-over by reaching from the top flange to the surface sparks on the pin shed. The glow at places of high density, as in the joints, gives rise to surface sparks with the largest insulators, and as the length of these sparks increases rapidly as the cube or fourth power of the voltage (see page 276), flash-over rarely takes place between the flanges, especially with very long sheds. The spark-voltage distance curve for large insulators—*i.e.*, large distances—will rapidly bend over, as in Fig. 14 (see also page 256).

The length of the surface brush † is influenced by the humidity of the air, though not sufficiently to affect the flash-over of small insulators. For medium-sized insulators the flash-over voltage is increased 3 to 9 per cent., and for the largest constructed the maximum increase is about 20 per cent. with increase of humidity. When the humidity is 100 per cent. moisture is deposited on the surfaces, and a lowering for all sizes will be produced. Temperature has little effect, as the spark voltage varies inversely with the absolute temperature.‡ A variation of 10 mm. in atmospheric pressure produces a difference of 2·4 per cent.

* J. Lustgarten, "Flash-over Voltages," *Electrician*, vol. 62, p. 374, 1908.

† With increase of humidity the gaseous ion becomes the focus of neutral molecules of water vapour which, on account of the "loading," requires a greater potential gradient to produce the necessary ionisation for the brush discharge.

‡ Kemp and Stevens, *Journal of the Institution of Electrical Engineers*, vol. 45, p. 689, 1910.

in the spark voltage between small electrodes,* so this will hold approximately with line insulators.

(*b*) *In the Wet State.*—Rain alters the appearance of the discharges, the alteration depending upon the amount and the direction of rainfall. With a fine drizzle and no wind the top surface becomes wet and the glow and surface brush disappear, but give place to glowing drops of water at the edge of the top flange. These point in the direction of the flux, and, becoming charged, are forced away with a velocity increased by the flux density and diminished by their size.

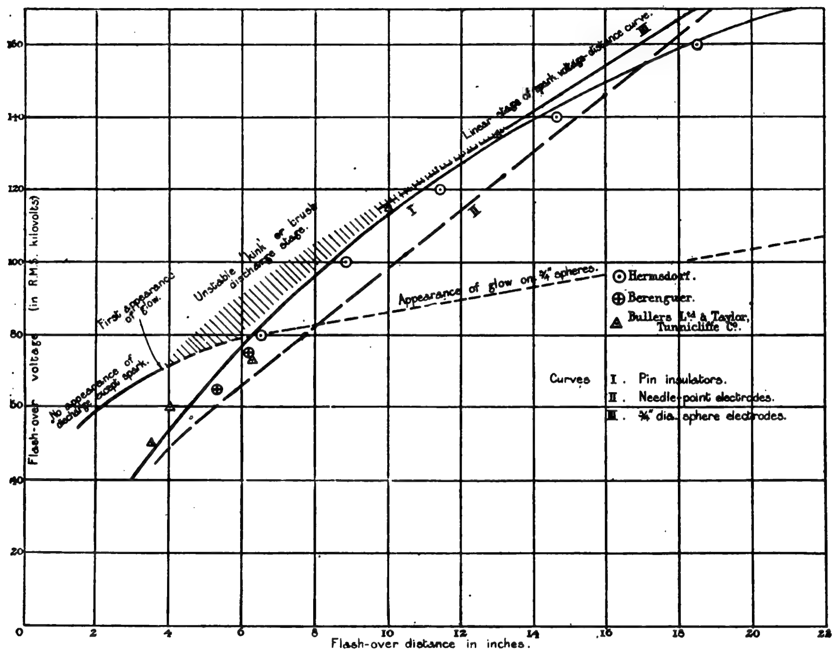

FIG. 14.—Flash-over Voltage-Distance Curves.

The flash-over voltage is reduced on account of the diminished spark distance and the point action of the elongated drops. With a more intense rainfall the brush discharges take place from glowing rain-drops of one shed to the moist part of another, and the spark selects the shortest path to these conducting places (Fig. 24). If the under surface of the top shed be also wet, there will be no glowing drops at this shed. On lowering the pressure and completely wetting the sheds, except inside the pin shed, there is no other discharge but the brush discharge to the bolt. With most of the surfaces wet the total

* Weicker, "Dissertation," *Königliche Sächsische Technische Hochschule*, Dresden, 1910.

Fig. 12.—Flash-over on Large Insulator by Surface Sparks.

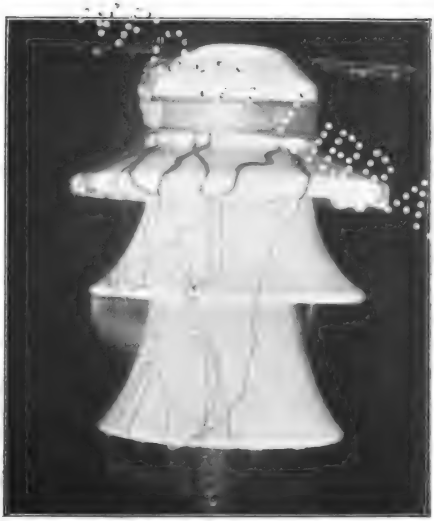

Fig. 15.—Brush and Spark Discharges on Insulator under Rain.

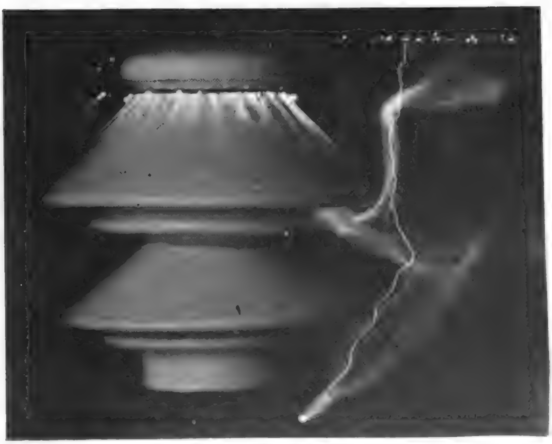

Fig. 13.—Surface, Pilot Spark, and Arc on Italian Insulator.

flux and the capacity are considerably increased, and if the pressure is brought up quickly whilst the insulator is still under rain, the flash-over will take place by surface sparks as in Fig. 15,* although the normal flash-over under rain takes place mostly through air between the sheds. When the rain stops the moist surfaces are

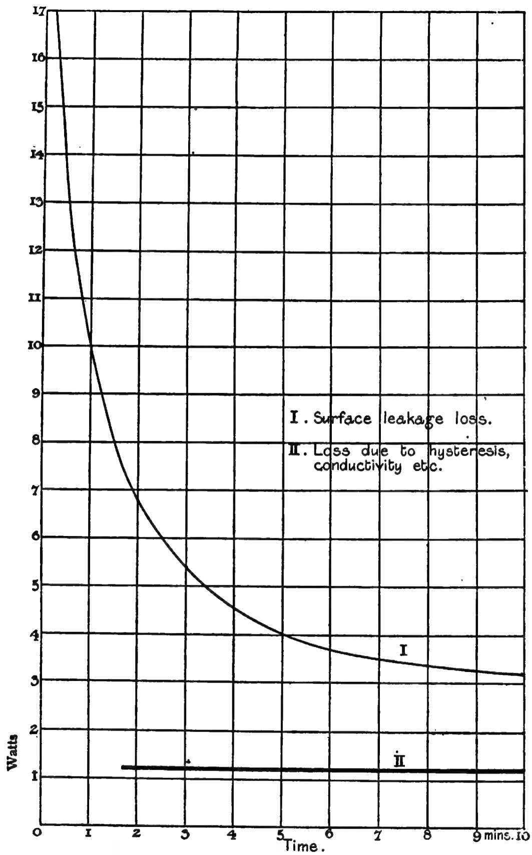

FIG. 16.—Curve of Leakage Loss and Time for a 13-k.v. Insulator in a Mist after Application of Pressure of 26 k.v.

soon dried by the heating effect of the leakage current and by the action of the electric field. While this is going on the fluctuating surface streamers may be seen between the moist parts. In a mist the drying action would be constantly going on. This is proved by the following experiment (see Fig. 16): A pressure of 26 k.v. was applied

* The sparks coming out black on the white porcelain surface in Fig. 15 is an interesting example of photographic reversal.

to a 13-k.v. insulator in a damp atmosphere. The leakage loss fell from 40 to 3·5 watts in 10 minutes. The pressure was increased by 50 per cent., and maintained for 5 minutes. Then, on reducing the voltage again to 26 k.v., the leakage loss was less than 3 watts, but gradually crept up to that value. Hence the insulation resistance of the insulator in a damp atmosphere is a function of the voltage.* If steam be blown against charged electrodes it is repelled away, the action being greater with pointed electrodes.

Insulators with the bottom shed close to the bolt have a fairly dry space within, so that with this shed moist on the outside a brush discharge may start in the bolt-hole at the line pressure. This has been observed in this country on damp days with the older form of insulator. An insulator which becomes wet by being in a damp atmosphere will show when quickly subjected to the line pressure a glow over the whole of the surface owing to the leakage current, but the drying action comes rapidly into play.

All these forms of discharge—namely, glow, brush, and spark—have a reddish tinge: they are less intense than those obtained with the insulator dry, because of the resistance of the water in series. Their actinic value being lower, much longer photographic exposures are necessary.

Protection against Arc Effects.

A high potential surge due to a direct lightning stroke or to induction in the neighbourhood of the line may cause one or more insulators to flash over, on account of the difficulty with which the charges travel along the line to the protective devices (arresters, etc.). The potential stresses set up may be sufficient to puncture one or more sheds of the insulator; this puncture results in the formation of the arc. There have been cases, however, where a shed of a large and long insulator has been shattered by lightning without puncturing the insulator and without producing a flash-over—the effect being similar to that caused by a hammer blow.† The arc tends to be drawn to an intense part of the electrostatic field, as can be seen in Fig. 13. Hence the end of the arc striking the pin tends to run up within the pin shed and, with great plant powers, the heat produced breaks the porcelain sheds from the bottom upwards. Since insulators are now designed to flash over —rather than to puncture—the question of affording complete protection against damage by arcs is important. A simple method has been devised by Nicholson. He uses two metal rings concentric with the insulator, the lower (of greater diameter than the insulator) attached to the pin, and the upper ring (somewhat larger than the neck of the insulator) suspended from and connected to the transmission line (Fig. 17). The rings serve as a safety-gap for the arc. The lower ring can be placed so high and close to the insulator as to reduce the flash-

* Weicker, "Dissertation," Dresden, 1910.

† Nicholson, *Transactions of the American Institute of Electrical Engineers*, vol. 29, part 1, p. 573, 1910.

over voltage, thus forcing the arc to pass to it from the upper ring or the cable. Fig. 18 shows the transference of the arc to the lower ring —no upper ring being employed. There is still the risk of damage to the head-piece, which might be obviated by the use of a larger upper ring instead of the small one suggested by Nicholson. Fig. 19 shows the manner of using the two rings. The dry flash-over voltage has been reduced from 114 to 102 k.v., and the wet flash-over voltage under standard precipitation is not less than the normal value without the ring, viz., 88 k.v. That this device has been effective has been shown by tests made on the 60-k.v. 3-phase transmission line of the Niagara, Lockport, and Ontario Power Company with a 30,000-k.w. arc at the line pressure. In no instance was an insulator damaged. With or without the small upper ring the arc would travel out on the cable a distance of 12 ft. in 4 seconds with a breeze of 3 miles per hour, but the scarring would be greatest where the arc first started. A large upper ring would save the cable or tie wires from the initial burning.

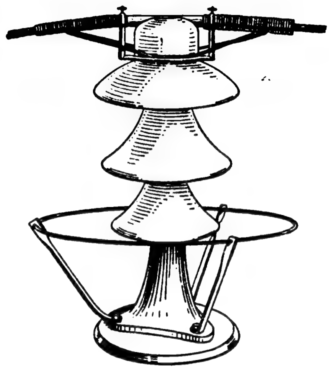

FIG. 17.—Long Shedded Insulator with Nicholson's Arcing Rings.

It is interesting to give the performance of the insulator used because the experience on this line has affected subsequent designs. The insulator* consists of 3 shells cemented together and has the following dimensions :—

Diameter of head-piece	... ...	$14\frac{1}{2}$ in.
„ intermediate shell	... ...	13 „
„ pin shell	... ...	11 „

The total height from the edge of the bottom shell to the top of the head, $19\frac{1}{2}$ in.; length of intermediate, 12 in.; and of bottom shell, 17 in.

Each shell had withstood a factory test of 75 k.v. for 3 minutes before assembling, but the complete insulator was not tested. Its dry flash-over voltage is 195 k.v., and wet 120 k.v. On testing with 195 k.v. there were many failures due to the high stress on the procelain. It must be noted that the test voltage is more than three times the line voltage—a safety factor much higher than used at the present day for 60-k.v. line pressures. The lower ring was then used; it reduced the dry flash-over to 160 k.v. and considerably diminished the tendency to puncture which generally takes place in the pin shell. Tests were

* Mershon, *Transactions of the American Institute of Electrical Engineers*, vol. 26, part 2, p. 1367, 1907.

made on 800 insulators first with and second without the ring—the flash-over voltages were 160 and 195 k.v. respectively; the pin shell failures with the ring were 3 per cent. and without 22 per cent. The ring employed was 26 in. in diameter, $\frac{3}{8}$ in. thick, and placed $2\frac{1}{2}$ in. above the edge of the bottom shed. This size and height was chosen so that under normal precipitation the arc would strike the ring and give a flash-over voltage of the same value as without the lower ring, and also a dry flash-over voltage of 160 k.v. as indicated. The ring placed $2\frac{1}{2}$ in. above the base reduces the effective length of the insulator. Therefore a shorter insulator has been designed, which replaces the topmost insulator of the line. The experience on this and on other lines employing mast-top pin insulators, without the overhead grounded wire, and without arcing rings, shows that more than three-fourths of the insulators broken were top insulators. The new design is of the same diameter but 6 in. shorter, and consists of four shells. Its dry flash-over voltage is 190 k.v., and wet 105 k.v. It is interesting to note that the dry flash-over is altered very little by lessening the length. The surface sparks on account of the longer pin shed and the smaller thickness of porcelain between the pin and line (giving a greater capacity), reduce the effective air distance from wire to bolt. An arcing ring provided on the new design reduces the dry test value to 160 k.v. (Fig. 20).

The earthed metal ring effects a redistribution of the field. It takes up part of the flux which would otherwise enter the pin shed, thus producing a less flux density and causing a more uniform distribution among the other shells, with less danger to all the shells. The large upper ring shown in Fig. 19 distributes the flux still more uniformly, and will relieve a surge of charging current due to sudden disturbances.

Metal Shed Insulators.

The use of a large upper ring in Fig. 19 suggests its extension to a metal shed. Fig. 21 shows the Hermsdorf patent metal-shed insulator. The upper surface of the ordinary insulator is practically conducting when wet. Its function is, besides the mechanical strengthening of the head of the insulator, to protect the other sheds against rain, and to provide a dry under surface. The metal shed of large diameter effectively protects the porcelain parts against wetting, and in dispensing with the weight of the porcelain head and also being shorter for a given line voltage, its weight and price are less. These advantages are greatest at voltages between 40 and 70 k.v., but below 25 k.v. they are not maintained. The diminution in leakage-path in this insulator is counterbalanced by the protection it offers to rain. Further, at the sharp metal edge the flux density is greater than with the corresponding porcelain head-piece, so that drops of water become more conical and will be urged with greater velocity outwards (see Fig. 42). The wet flash-over voltage is influenced by the direction in which the drops fall, and we should expect that the metal shed

FIG. 18.—Insulator with Lower Ring only, showing Arc Flashing to Neck of the Insulator.

FIG. 10.—Insulator with Large Upper and Lower Rings

insulator will give a value not much less than when dry. The insulator in Fig. 21 (without the lower ring) has a dry flash-over voltage of 75 k.v. and wet 70 k.v. A larger insulator for 44 to 50-k.v. line pressure has a dry flash-over voltage of 110 k.v. and a wet value of 98 k.v. Even in the heaviest rain the pilot spark starts from the inside surface rather than from the edge. At the edge of the head-piece of the all-porcelain insulator there is a fluctuating variation in the flux density, as some points are wetter than others, but at the edge of the metal shed insulator the flux distribution is practically uniform. Thus the wet flash-over voltage for the metal shed insulator is more definite than for the all-porcelain insulator. The flux in passing from the bolt to the top shed will be more uniform with the metal shed insulator than with the other. In a comparative wet test of the two types for 80-k.v. line pressure, the ordinary insulator flashes over at

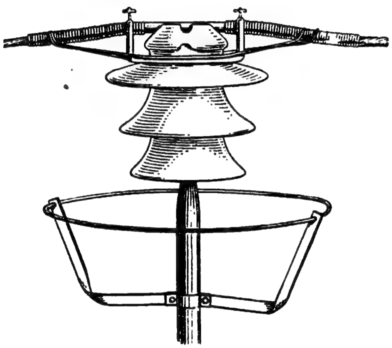

FIG. 20.—Short Shedded Insulator with Nicholson's Arcing Rings.

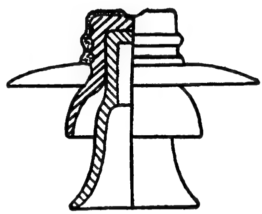

FIG. 21.—Hermsdorf Metal Shed Insulator.

130 k.v., whereas the other shows only the initial discharges. Heavy surface sparks occur on the ordinary type, and are preceded by brush discharges at a much lower voltage than on the metal shed insulator. Since the brush discharges occur later on the latter, and since the production of surface sparks is minimised (being less wet), the insulator can be made shorter. The dimensions and weight for 80- and 55-k.v. line pressures are given below in Table III.

The distribution is also better for the metal shed insulator in the dry state. The flux density in the neck and top of the bolt-hole is much lessened, as the flux starts from a wider area, viz., from the inside of the shed, thus increasing the safety factor against puncture and hampering the production of surface brush discharge. The following test may be cited to show the improvement in the electrostatic conditions. With a line wire simply resting in the neck of an ordinary insulator the dry flash-over voltage was 109 k.v. Attaching a tie-wire round the neck increases the value to 116 k.v., and with a metal cap affixed to the head 123 k.v. Replacing the porcelain shed by a wide

metal cover to give the same sparking distance, the flash-over value rose to 126 k.v.

The shape of the intermediate porcelain shell—namely, its convexity to the metal—is explained by the discussion on design, pages 245 and 246. The nearer the porcelain shell is to the bolt, where the flux density is greater than adjacent to the shed, the greater will be the total flux produced. Its convexity gives it also an excellent protection against rain.

The loss due to displacement current is not greater than for the ordinary porcelain insulator of the same voltage.

An arcing ring, of about the same diameter as the metal shed, fixed to the bolt, will protect the porcelain against power arcs. The large cooling surface of the metal shed would prevent its being fused by the arc. Used in conjunction with a metal basket, instead of a ring, it would offer a good protection against breakage by stone-throwing.

TABLE III.

	Ordinary Insulator.		Metal-shed Insulator.	
	80 k.v.	55 k.v.	80 k.v.	55 k.v.
Diameter	39 cm. (15·4 in.)	28 cm. (11 in.)	50 cm. (19·7 in.)	32 cm. (12·6 in.)
Height	49 cm. (19·4 in.)	34 cm. (13·4 in.)	39 cm. 15·4 in.)	25 cm. (9·8 in.)
Weight	19 kgm. (41¾ lbs.)	8·3 kgm. (18 lbs.)	13·8 kgm. (30 lbs.)	4·2 kgm. (9¼ lbs.)

Shackle Insulators.—Shackle insulators are used for curves, dead-ends, and similar points in a transmission line where the pull is too great for the ordinary pin insulator. Fig. 22 is for a line pressure of 30 k.v., and withstands a pull of 12,000 lbs. For heavier loads the insulators are used in multiple. To obtain maximum strength of this type, if the pin used be allowed free play in the hole and not fit snugly, only the porcelain at the point between the wire and the pin will be under compression. For higher voltages shackle insulators are used in series. On a 20-k.v. transmission line * at Lobito, Portuguese East Africa, three 10-k.v. shackle insulators are used in series for dead-ending, etc. The suspension strain type is very suitable for points where the shackle insulator would be employed (see page 257). A simple form of suspension strain insulator shown in Fig. 23 is used in the British Navy for insulating the aerial wires in connection with wireless telegraphy. It withstands a compression test of 11 tons.

* Equipped by Messrs. Johnson and Phillips.

Suspension Insulators.

General Remarks.—The increase in line voltage to 110 k.v.* has brought about the introduction and development of the suspended type of insulator on account of the large increase in weight and cost of the

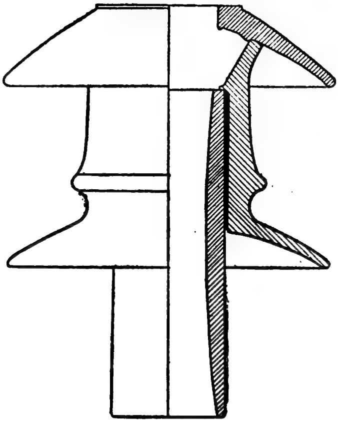

Fig. 22.—Shackle Insulator for 30 k.v. (Locke).

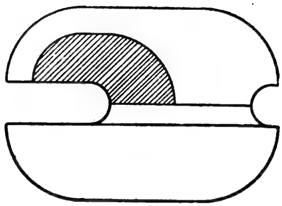

Fig. 23.—Strain Insulator used in the Navy for Aerial Wires.

pin insulator required. Above a pressure of 50 k.v. the weight and size of the pin insulator increase rapidly. The weights of insulators of some typical European transmission lines are given below :—

Table IV.

Line.	Pressure in Kilovolts.	Weights of Pin-type Insulators.
Heimbach-Aachen ...	33	7½ lbs.
Gromo-Nembro	40	5 "
Albula Works—Sils-Zurich	50	16½ "
Orlu-Toulouse	55	28½ "
Ventavon-Brillanc... ...	60	28½ "
Molinar-Madrid	66	25½ "

The Heimbach-Aachen line was an early equipment. The Spanish transmission line (Molinar-Madrid) is equipped with 3-piece insulators

* A line of 135 k.v. is at present under construction (see page 259), and higher pressures will be only a question of time until corona on the line wires will be the next question to consider.

14 in. diameter and 15 in. high.* On page 251 the details of the Niagara, Lockport, and Ontario insulator are given; its weight is 59 lbs.

The large increase in size is necessary to provide a sufficient spark distance to counterbalance the influence of surface sparks which are produced by large capacities. In Fig. 14 the curve shows the relation of spark distance (*d* of Fig. 24) and the flash-over voltage of insulators of practically the same type from English, German, and Spanish firms.† Curves for needle-points and ¾-in. spheres are also plotted for comparison. It was pointed out on page 247 that for intermediate sizes a combination of the brush discharge and surface sparks causes flash-over, and for the large—the surface sparks.

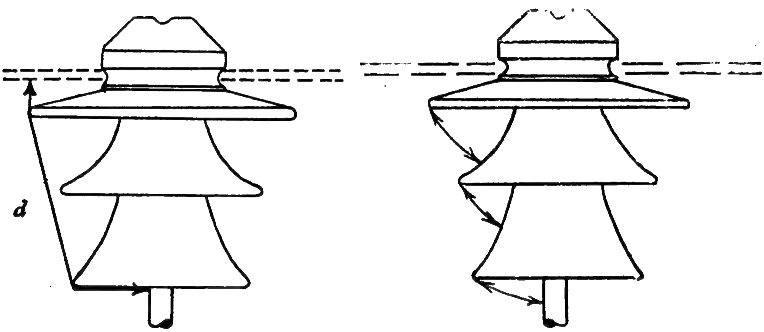

FIG. 24.—Spark Distance (*d*) for Insulators in (A) Dry State, (B) Wet State.

As the latter vary in length as the third and fourth power of the voltage, they will cause the curve in Fig. 14 to bend over rapidly. (The curve will thus cut the curve for needle-points.) The size and the weight of the insulator will increase almost at the same rate, namely, the third power of the voltage. The price will have a similar relationship. The following are the weights and prices of pin insulators from 50 to 80 k.v.‡ :—

TABLE V.

Line Pressures.	Weight.	Price.
50 k.v.	14 lbs.	4·2 shillings
60 "	22 "	8·0 "
70 "	29 "	11·5 "
80 "	42 "	19·7 "

* Weicker, *Helios*, vol. 17, Nos. 28–30, 1911.
† Taylor, Tunnicliffe & Co.; Bullers, Ltd.; Hermsdorf Porcelain Company; and Berenguer.
‡ Hermsdorf Works.

The weight and price of the suspension units, on the other hand, will increase linearly with increasing voltage (see page 266), each disc added for increased line pressure being identical. If the weight-voltage curves for the two kinds—pin and suspension—be plotted, they will intersect between 50 and 60 k.v. (according to the types of suspension units selected). The intersection of price-voltage curves is between 60 and 70 k.v. (The price of the suspension units for pressures less than 60 k.v. is greater on account of the metal parts.) Taking into consideration the necessity of a higher tower, the extra cost of which is counterbalanced by the less cost for the cross-arms and smaller maintenance cost,* 60 k.v. may be taken as the pressure at which the suspension insulator becomes economical. As an instance of its adoption for pressures between 60 and 70 k.v., the 60-k.v. Groba (Saxony) transmission line under construction will employ 3-unit suspension insulators. For the 66-k.v. Northern Hydro-Electric Company (North Wisconsin) line the same number of suspension units

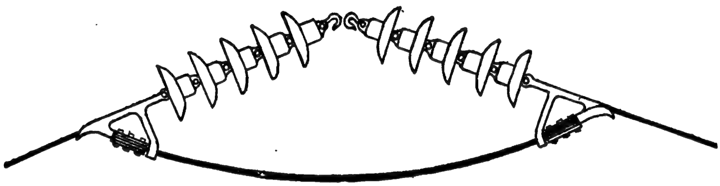

FIG. 25.—Dead-ending Arrangement (Locke).

is being used.† Fig. 27 shows the suspension insulators in use. They hang vertically beneath the cross-arm and are allowed to swing freely. At intervals of about 1 mile the line is anchored to strain towers. There are about 5 to 10 ordinary towers to one strain tower. The strain insulator employed is usually larger, as it undergoes greater mechanical stresses. Fig. 25 shows the method of attachment with the line wire hanging below the insulators. On account of the surfaces being wetter under rain, a greater number are used in series than in the suspension group. These strain insulators are used also at corners and for dead-ending the line.

Advantages.—The suspension type has other advantages. The unit construction is of paramount advantage, for if at any time it is desired

* W. T. Taylor, "Modern Long-distance Transmission of Electrical Energy," *Journal of the Institution of Electrical Engineers*, vol. 47, p. 174, 1911.

† The 44-k.v. transmission line from Lockport to Western Avenue (Chicago) has added suspension insulators to secure additional carrying capacity for the increasing loads. The original lines in duplicate possess six pin insulators. Two 3-unit suspension type are hung from the bottom cross-arm, and a pin insulator placed at the peak of poles gives now three separate circuits. The last wire takes the position of the original ground wire. The arrangement should also substantiate the claims of those who advocate the use of a ground wire to prevent lightning disturbances in the next lightning season. The Nicholson arcing-ring device has been adapted to all the insulators on the south side of the pole line. (See *Electrical World*, vol. 57, p. 171, 1911.)

to increase the line pressure the only change is to add the standard unit. Localities such as sea-coasts and near chemical factories requiring extra insulation can have an extra safety factor by addition of a unit. Further, for such places the suspension type is better cleansed by rain. This is not so with the pin type; it necessitates a change of form and size. Moreover, with the latter, if a shed of the insulator is damaged the whole insulator must be replaced, but with the suspension group only the damaged unit requires removing. And whilst the damaged pin insulator may cause a shutdown, the safety factor of the group is sufficient to prevent it. Its simple construction and its comparatively small size give no difficulty in manufacture. Hence there is the advantage of shorter time of delivery and of the possibility of keeping a large number in stock.

The suspension group has a smaller capacity than the pin type, this capacity diminishing as each unit is added, but increasing for the large sizes of the pin type for higher line pressures. A greater flash-over distance gives a higher ratio of flash-over voltage to line voltage for a suspension group than for a pin insulator. Although a wide pin insulator gives a better rain protection than the narrower but larger suspension group, yet the number of dry surfaces of the latter gives a smaller surface leakage loss.

The suspension type has none of the mechanical difficulties of the pin and the cross-arm in the pin type. The manner of suspension allows the line wire to move freely under wind pressure. The flexible connection between the conductor and cross-arm should minimise any tendency to crystallisation of the line wire (especially with aluminium), which has been known to take place where it is fastened to the neck of the insulator.*

The suspension of the wire below the earthed cross-arm causes less disturbances of the line due to lightning. Many lines which have changed from the lower pressure with the pin type to the higher pressure with the suspension suffer less from lightning. The addition of the earthed wire between the masts has lessened the disturbances still further. This wire in some cases is used to take the longitudinal strain of flexible mast construction.†

Types.—There are two distinct types in practice, from the manner in which the units are supported. One type—the link insulator—has two interlinked, semicircular holes for tie wires. Fig. 26 is one form. The second type has the metal parts concentric (Fig. 32, 34, and 35). These consist of a metal cap and a bolt cemented to the porcelain. A third type of suspension insulator, which has not come into use—at any rate for line work—is similar to the first type, but the tie wires are not interlinked. Electrically the type is better because of the lessened flux density and capacity, but mechanically they are much weaker. In the latter the porcelain is in tension, but in the former in compression.

* Buck, *Transactions of American Institute of Electrical Engineers*, vol. 26, p. 981, 1907.

† Matthews and Wilkinson, *Journal of the Institution of Electrical Engineers*, vol. 46, p. 562, 1911.

(*a*) *Interlink Type.*—With the first type the interlinking has the advantage that in case an insulator breaks the tie wires will still hold the other units together, and, with the ample safety factor, prevent a shutdown. But against this there is the possibility that the tie wires may not interlink when one or more units puncture, and an arc may destroy the links. The tie wires may break from the constant rubbing in the holes and from a possible corrosion by ozone produced by any electric discharge in the holes (see Fig. 41).

Fig. 26, the Hewlett form of the General Electric Company, is a flanged disc with enlarged central portion.* It is made in two diameters, 6 in. and 10 in., of lengths 2½ in. and 2¾ in. respectively. The larger unit has a dry flash-over of about 80 to 95 k.v., and wet

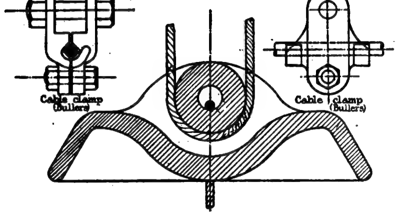

FIG. 26.—Hewlett Interlink Type.

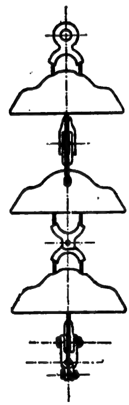

FIG. 27.—Suspension Series.

50 to 56 k.v. It is rated for a line voltage of 25 k.v. Four in series (Fig. 27) are being used on the 80-k.v. Victoria Falls and Transvaal Power Company's transmission line (length 45 miles) in South Africa; but on a new line of the same company five are being specified. On a 100-k.v. transmission line of the Central Colorado Power Company † four are employed, and for the Grand Rapids and Muskegon Power Company five in series for 110 k.v. The 135-k.v. line, ‡ Cook Falls to Flint, and Battle Creek, Michigan (total length of 190 miles), under construction, will have 8 units § and a group height of 52 in. The 6-in. diameter unit gives a dry flash-over of about 50 k.v., and wet 30 k.v. Two units in series are used at Hayle, Cornwall, on a 10-k.v. line of Edmundson's Electricity Corporation.

* Manufactured in England by Messrs. Bullers, Ltd.

† *Electrical World*, vol. 55, p. 202, 1910. ‡ *Ibid.*, vol. 56, p. 98, 1910.

§ Since the reading of the paper, the author notes that the line is operated at 140 k.v. and is equipped with ten 10-in. Ohio Brass Co. type insulators (Fig. 32). *Ibid.*, vol. 59, p. 795.

Fig. 28 * shows a recent production of the interlink type, used on the 60-k.v. transmission line, Dessau-Bitterfeld. It has the advantages of increased spark distance, better rain protection, and the use of wire ribbon, which is easier to thread through the holes than the ordinary circular wire. The strain insulator (Fig. 29) of the Hewlett "fish-tail" pattern is made in the same diameters. In all the above lines the number of strain units and suspension units is the same. Both suspension and strain insulators of the largest diameter are tested to 3 tons (compression), and the smaller to 1½ tons. Details of the clamps, etc., for the 80-k.v. Victoria Falls line mentioned are shown in Figs. 30 and 31.

(*b*) *Cemented Type.*—Figs. 32, 35, and 37 show the various forms of this type. The design of the cemented type can be made so that the porcelain is partly in compression and partly in tension. When an insulator of this type fails under mechanical stress, it is by shear and tension combined. By altering the relation of the bolt and bolt-hole surfaces, the bolt may be made to pull out when the shearing strength of the cement is reached. The following experiments conducted with the insulator shown in Fig. 35 show the physical characteristics of the cemented type. Immersed in a freezing mixture at — 7° C. and then plunged into hot water at 90° C. showed no effect on its strength electrically and mechanically; nor when changing the order of immersion. There was no difference when immersed for 5 minutes at 0° C. and then for the same duration of time at 80° C.—the operation repeated a hundred times. Even heating the metal cap with a Bunsen flame to 130° C. and then immersing in water at 0° C. produced no difference. When all the sheds were knocked off the mechanical strength was practically unaltered.†

Fig. 32 is the Ohio Brass Company pattern,‡ and is similar to that described in a previous Institution paper.§ It is 11 in. in diameter, and has a dry flash-over of 85 to 90 k.v., and wet 50 to 56 k.v. Under oil it punctures at about 130 to 140 k.v. The dry test on the four units is given as 300 k.v., and wet about 200 k.v. The first 100-k.v. line in India (44 miles in length)—that of the Tata Hydro-Electric Power Supply Company, Bombay—will use six 10-in. diameter insulators of this pattern for suspension on the intermediate towers and six 10-in. diameter interlink (Fig. 32) insulators on the anchor towers; details of suspension are shown in Figs. 30, 31, and 33.‡ The ultimate breaking stress of these units is about 5 tons, the routine test being 3 tons. For the 100-k.v. line of the Central Mexico Light and Power Company§ 6 units are used. Taylor gives three as that used on a 60-k.v. line. On the 110-k.v. line of the Hydro-Electric Power Commission of Ontario, 8 units of similar design,|| and 10 for strain, are employed. The latter

* Made by Hermsdorf Works.
† Weicker, *Elektrotechnischer Zeitschrift*, December 14 and 21, 1911.
‡ Made by Bullers, Ltd.
§ W. T. Taylor, *Journal of the Institution of Electrical Engineers*, vol. 47, p. 174, 1911.
|| Made by Hermsdorf Works.

have a more massive cap (about $\frac{5}{8}$ in. longer) and have been tested to $4\frac{1}{2}$ tons. The dry flash-over voltage of the suspension unit is given as 84 k.v., wet 50 k.v.; each unit adds 70 k.v., and 40 k.v. wet respectively.

Fig. 34 is the Duncan insulator * of the Locke Company, made up of two shells. It has the advantage of increased dry surfaces in unfavourable weather. The largest insulator has an outside diameter of 14 in. and an inner of 6 in. The shells are tested with 90 and 60 k.v. respectively, the unit being specified for a 25-k.v. line pressure. Four units are used in series on the 110-k.v. line of the Stanislaus Electric Power Company, San Francisco,† and four on the 100-k.v. line of the Great Western Power Company, California.

Fig. 35—the Hermsdorf form—is like the conventional pin insulator. It is made in three sizes for line pressures of 20, 25, and 30 k.v., but the last two sizes are the most suitable for high pressures. The intermediate size has a dry flash-over voltage of 88 k.v., wet 51 k.v.

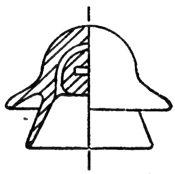

FIG. 28.—Hermsdorf Interlink Type.

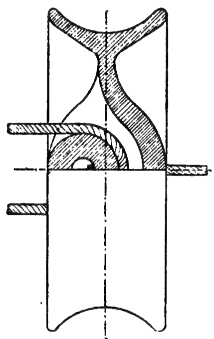

FIG. 29.—Hewlett Interlink Type.

Two units are sufficient for 50 k.v., and three for 70 k.v. The largest size has a dry flash-over of 100 k.v., and wet 61 k.v., and is used on a 70-k.v. transmission line in Guadalajara (Mexico), three units in series.

Fig. 36 is a later Hermsdorf type, with a sunken cap, which gives the unit greater mechanical strength and enables the units to be brought nearer together. A mechanical test shows that the first fracturing of the porcelain occurs at $5\frac{1}{2}$ tons: at 8 tons the bolt is torn out. Its dry flash-over voltage is slightly less than that of the previous type, but its wet value is better with increasing number in a group. It is to be employed five in series on the first European 110-k.v. transmission line—Lauchhammer-Gröditz. The total height of the group will be 3 ft. 9 in., whereas on the American lines the height of suspension groups is 4 to 6 ft. Fig. 37 is a metal-shed form

* *Transactions of the American Institute of Electrical Engineers*, vol. 29, part 1, p. 615.

† Mathews and Wilkinson, *Journal of the Institution of Electrical Engineers*, vol. 46, p. 562, 1911.

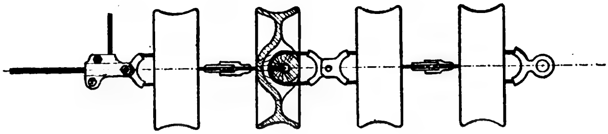

FIG. 30.—Hewlett Interlink Type in Series.

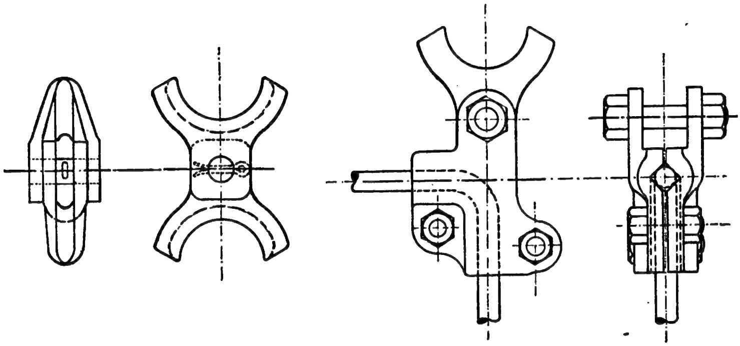

FIG. 31.—Details of Clamps (Bullers).

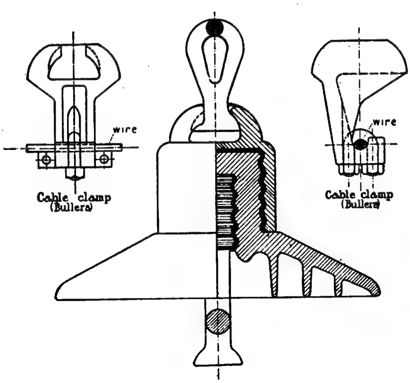

FIG. 32.—Ohio Brass Co. Cemented Type.

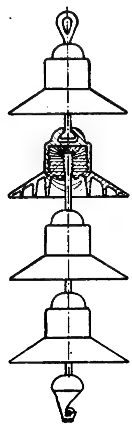

FIG. 33.—Suspension Series.

of Fig. 35. Its dry flash-over is the same, but its wet flash-over is 68 k.v. In comparison with the all-porcelain insulator the wet flash-over voltage improves with the number in series. Fig. 38 is the newest

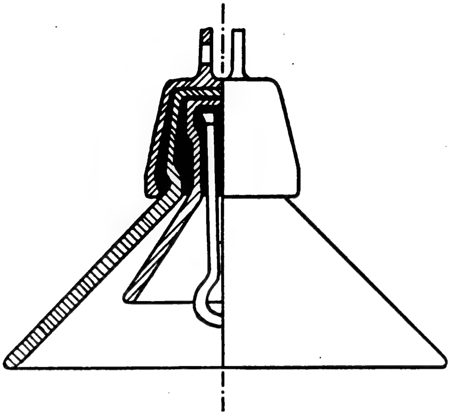

FIG. 34.—Duncan Type.

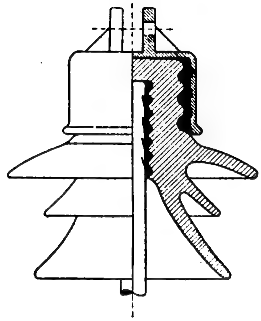

FIG. 35.—Hermsdorf Type.

metal-shed form of Fig. 36. By curving the metal shed better mechanical protection and provision against weather are obtained.

Electrical Considerations in Design.—The principles of design of pin insulators discussed on pages 245 and 246 are in the main applicable to the

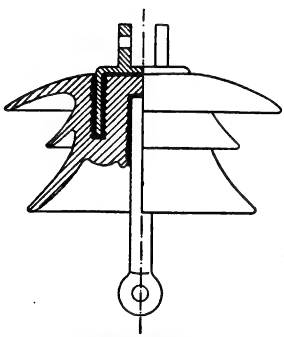

FIG. 36.—Hermsdorf Sunken Cap Type.

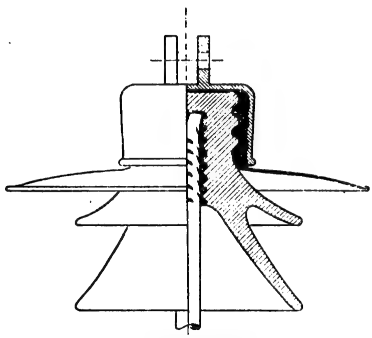

FIG. 37.—Hermsdorf Metal Shed Type.

suspension insulator, for the latter may be considered as a modification of the former. If small discs of metal, in duplicate, be interposed at the cemented joints of the insulator shells, the flux distribution will not be sensibly altered, as the equipotential surfaces before introducing the metal are practically coincident with the cement layers.

On separating the shells, with the discs attached on either side, and electrically connecting the discs, we get the series formation of suspension units. It is only necessary to make the shells of uniform size and to modify the electrode to produce the types shown in Figs. 26 to 38.

The separation of the shells has introduced large air-spaces, thus the total capacity and charging current decreased considerably. The distribution of flux density is more uniform than before separation, and therefore there is less liability to puncture (see page 252). For a given voltage the flux density in the shortest distance between the electrodes of the unit depends on the total thickness of porcelain for the *n* units of the series; the larger number of units which can be used in contrast with the number of sheds in the pin type diminishes the flux, the flux density, and the puncture risk. Each unit must itself have sufficient thickness, so that flash-over takes place before puncture. This is one reason for the employment of two shells in the Duncan form (Fig. 34). The difficulty of boring the interlink type makes the thickness of porcelain between the links variable and produces a greater percentage of punctures than in the cemented type. This greater percentage, together with the difficulty of boring, brings up the price of the interlink type.

As the separation of the units increases, the flux density at the electrodes diminishes and then becomes constant. The distance at which it becomes constant depends on the shape of the unit. If we suppose that the flux, for a given voltage, varies inversely with the *n* units,* then to attain the same flux (and flux density) as for one unit a voltage *n* times is required. An equivalent statement is that, the capacity being reduced *n* times necessitates a voltage *n* times as great to produce the same displacement current. That is, as the line pressures are increased the addition of units gives still the same displacement current. Contrast this with the pin-type insulator, which increases in capacity for the higher line pressures.

The relative size of the electrodes is a factor influencing the flux density at the neck of the unit. The metal cap in the cemented type tends to produce a better flux distribution than in the interlink type. (The sunken metal cap, Fig. 36, removes the high gradient from the top shed to the under surface of the pin shed—hence the wide air-space to counteract it.) The metal sheds of Figs. 37 and 38 distribute the flux better still, lessening the tendency for glow formation. The smaller thickness of porcelain and smaller size of the electrodes of the interlink type start the glow earlier than in the cemented type. Its capacity is also greater. Under rain the initial discharges occur sooner than with the other type. Narrow air-spaces between the shells (as in the Duncan unit) and between the sheds (in the petticoated or multi-shed unit), where the flux densities are high, tend to formation of glow.

* This is not strictly true (see page 265), but when the top sheds are wet or are of metal it is, after the first unit, approximately true, the metal sheds acting as parallel equipotential planes between cross arm and line wire.

FIG. 40.—Sparking over Flanges of a Suspension Series under Rain.

FIG. 41.—Arcing over Individual Units in the Dry State, showing the Glow in the Holes.

FIG. 42.—Showing Point Action of Drops of Water on Suspension Units under Rain. Top Unit not Grounded.

FIG. 45.—Sparks outside Frozen Snow.

FIG. 46.—Sparks adjacent to a Long Icicle at a Temperature below Freezing-point.

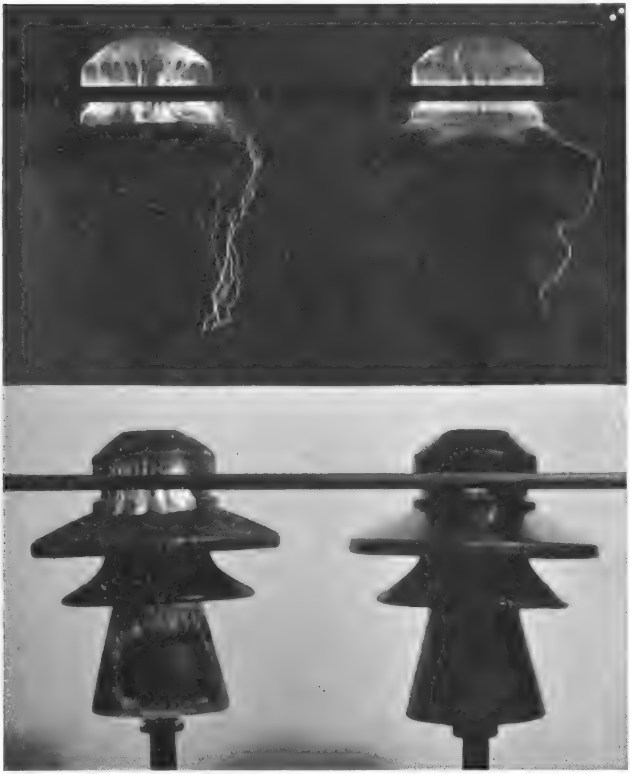

FIG. 47 (A and B).

A.—A clean and a soot-blackened insulator in the dry state both flashing over at 93 k.v., showing also the character of the initial surface discharge.

B.—Insulators as in A, but moistened by steam, showing surface discharges and flash-over at 50 k.v. on the soot-blackened insulator. The clean insulator shows very little glow at the neck.

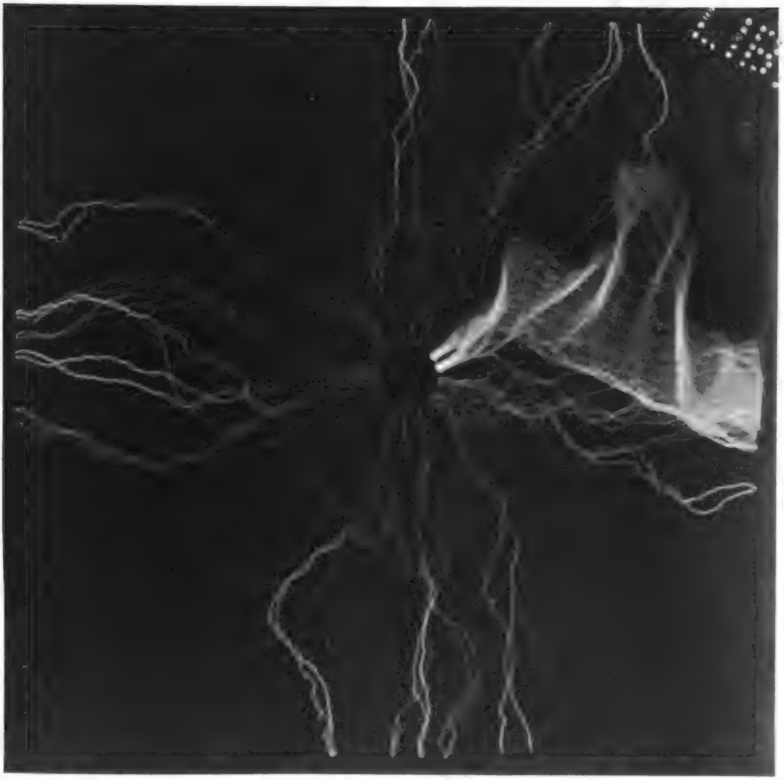

FIG. 48.—Surface Sparks and Arc on a Glass Plate at 60 k.v.

In the early designs of suspension unit a disc type without petticoats was employed. To obtain a high flash-over large diameters and great separation of the units were tried, but it was readily seen that the full sparking distance could not be utilised. This is on account of the surface sparks * produced on the upper and lower surfaces (see Fig. 39). A small thickness of the shell and a large diameter tend to establish these sparks, and thus the unit flashes over, for the same sparking distance, at a less voltage than when caused by a brush discharge in air-path direct. It is obvious from our discussion on page 247 that if the unit flashes over by the surface spark it will be true also for the series; especially when we take into consideration that the spark distance (over surfaces) varies with the third to fourth power of the spark voltage. In the Duncan unit the two shells force the brush streamer to take an air-path, but the large diameter (14½ in.) gives rise to the surface spark. The addition † of petticoats, as in the type of Fig. 32, raises the sparking voltage of the unit: for instance, with a 10-in. diameter disc the petticoats increase it 40 per cent., in addition to increasing the surface resistance; in wet weather especially its characteristics are better than for the plain disc. Under rain, brush discharges taking place between the petticoats (as in Fig. 15 for the pin insulator) cause flashing over.

For the same sparking distance the inclination of the shed of the unit has little effect for small diameters, but lowers the dry flash-over voltage for large. In the case of the latter, it disadvantageously increases the height of the series.

Distribution of Potential Gradient of the Series.—In passing from the lowest unit to the topmost, the flux (especially that part taking the long air-paths) reaching successive electrodes is not the same. Evidently for the middle units the flux density is less than for the outer units, and the divergence will be greater the greater the number in series. The divergence will also depend upon the distance apart of the units—namely, upon whether the ultimate flash-over takes place over the whole series as in Fig. 40, or across each individually as in Fig. 41. The flash-over voltage for one unit (Fig. 32) is 90 k.v., the addition of another increases it by 70 k.v. (which is explained by a diminution ‡ of spark distance, but at the sixth unit the increment is only 30 k.v. If the distance between the units be increased so that flash-over takes place across each unit, the spark voltage will be higher and the diminution of the increments is not so marked. The metal shed § unit causes a less

* Austin, *Proceedings of the American Institute of Electrical Engineers*, vol. 30, p. 1320, 1911, wrongly attributes the surface sparking characteristic to surface resistance. (See results with sooty insulator, Fig. 47 A and page 241.)

† Though the addition of the petticoats increases the total flux, for a given voltage, *before* discharges take place, it is afterwards smaller than for a plain disc.

‡ For one unit 90 k.v. is for the flash-over distance from cap to bolt; for the two units 160 k.v. from cap of first unit to bolt of second across the flanges. The spark distance from the cap of one unit to the *cap* of the next is slightly less. The bottom-most unit, in all cases, has the shortest spark distance.

§ A metal sheet dividing an all-porcelain series in two halves would cause a more uniform distribution and increase the increments; incidentally it would raise the voltage and protect the lower units from rain.

divergence in the flux densities of the units, on account of a better distribution of the flux, hence the increments after the second unit will be more uniform.

It is seen, therefore, that the relation of dry flash-over voltage is not proportional to the number of units. But the safety factor against flash-over (*i.e.*, ratio of flash-over to line voltage) is made smaller for higher pressures, hence as a first approximation the number of units is proportional to the line voltage.

Under rain, with the top surfaces wet, the flux distribution is more uniform. With a wide separation of the units the distribution of gradient is more uniform for the intermediate units. The *brush discharges* from the water-drops at each flange to the cap or the bolt below for Fig. 35, or from flange to flange (Fig. 40), cause ultimate sparking. Hence the increments for spark voltage with addition of units are practically uniform. For instance, the unit of Fig. 32 gives a wet test value of 53 k.v. from flange to bolt, and approximately 45 k.v. for each unit added.* (A wet test from flange of first to cap of second unit gives 49 k.v.; for the last unit from flange to wire 40 k.v.) Hence the curve of (wet) flash-over voltage and number of units is practically linear. This is a great contrast to the pin-type insulator. Thus the factor of safety—namely, ratio of wet flash-over voltage to line voltage—is higher for a suspension series for 110 k.v. than for a pin-type insulator of even 60 k.v.

Protection against Arc Effects.—Flashing over individual units is not desirable, as large power arcs tend to fracture the porcelain. Also, the flash-over voltage, when the arc takes the path, as in Fig. 33, is less than that when the arc passes over each individual unit from cap to cap, thus providing additional safety against puncture. To force the arc over the series the above considerations must be taken into account in the design of the series. These are as follows:—

1. Sufficient thickness of porcelain.
2. Medium diameter.
3. Petticoated or multi-shedded.
4. Small inclination of shed.
5. Metal cap or, better, metal shed.
6. Not too wide a separation of the units, nor too great a height of unit.

To safeguard suspension insulators the arcing rings mentioned on page 250 can be utilised. For instance, for six units of the type shown in Fig. 40 a ring on the topmost cap, another on the line-wire clamp, together with one on the middle unit should amply protect the series from a large power arc. The metal shed units in Fig. 35 do not insure the arc passing from metal to metal, but it is otherwise with the

* The upper unit in Fig. 42 shows the glowing drops more pronounced than in the lower unit. This is on account of the hook not being grounded; both terminals of the transformers were insulated, owing to breakdown of the leading-out tubes at 130 k.v. when one terminal was grounded. When the top unit is grounded no such difference in flux density is observed. (See also Weicker, Helios, No. 30, 1911.)

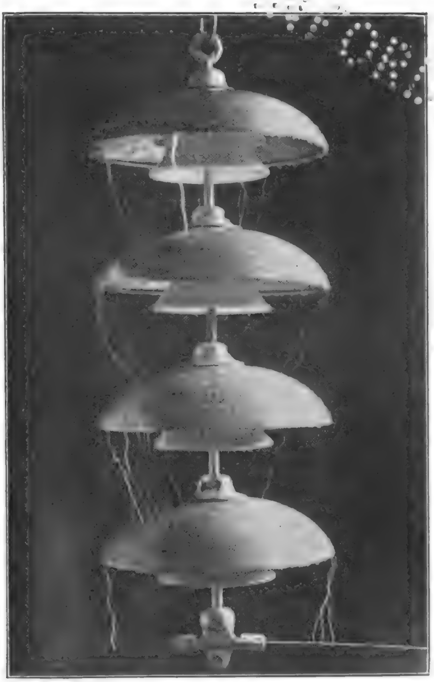

FIG. 38.—Hermsdorf Metal Shed Type with sunken Cap, showing Sparks clear of the Porcelain under Standard Precipitation.

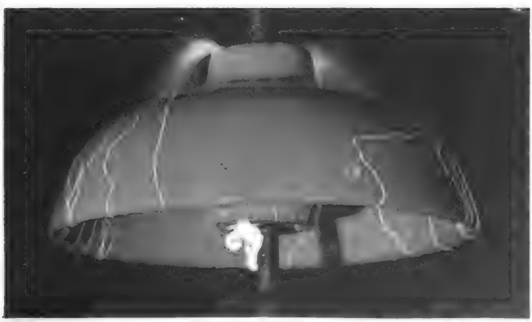

FIG. 39.—Surface Sparks on Disc Type in Dry State.

sunken cap (Fig. 38), as the units can be placed nearer together. The curve of flash-over voltage and number of units is practically linear, which is the case with the ordinary porcelain units only when wet. The difference between the dry and wet flash-over voltages with the latter amounts to 40 per cent., and this is even greater when the under surfaces are wet with driven snow. With protecting rings the difference is 20 per cent., and with these curved * metal shed units 12 to 15 per cent.

Testing of Insulators.

Measurement of Voltage.—The equipment of the testing laboratories of electrical porcelain works should be such as to be able to carry out two kinds of tests. The one consists of investigation work on the characteristics of new designs when subjected to the conditions in practice; and the other comprises guarantee tests on representative samples selected by the purchaser, and puncture tests on duplicates. The laboratories should be equipped for mechanical and also chemical tests, the apparatus for the former to deal with compression, tensile and bending strengths of the insulator, and for the latter to examine the raw materials and to lead to further improvement in the porcelain. Various plants have been described in the technical press.† In view of the increasing demand for high pressure many have installed transformers up to 300 k.v. The Victor Works of the Locke Company possess three transformers, each of 250 k.v. and 200-k.w. capacity; the Hermsdorf includes three of 100 k.v. and a fourth of 200 k.v., and are extending to a fifth of 500 k.v. In the high-tension laboratory of the Manchester School of Technology a transformer of 120 k.v. and 30 k.w. is employed for research. The equipment for control and measurement of the pressure have been previously described in an Institution paper.‡

There are three methods of measuring the pressure: (1) by transformer ratio, (2) by the Kelvin electrostatic voltmeter reading to 100 k.v. and (3) by a spark-gap. In the first method the pressure of the primary is obtained on a Kelvin electrostatic voltmeter (with mirror attachment) and a scale length of 3 ft., corresponding to 120 volts. The range of the voltmeter is increased to 600 volts by a resistance of 100,000 ohms placed across the primary and tapped in five sections. A high resistance (20,000 ohms per kilovolt) placed on the secondary winding of the transformer enables the same voltmeter to read up to 60 k.v. Oscillograph records and the spark-gap enable the maximum values of the pressure to be determined.

With regard to the spark-gap, there is a tendency to measure voltage by the needle-point spark-gap standardised by the American Institution

* Weicker, International Congress of Applied Electricity, Turin, September, 1911.

† *Electrical Review*, vol. 62, p. 401, 1908. Messrs. Taylor, Tunnicliffe & Co. Weicker, *Electrician*, vol. 61, p. 51, 1908, Hermsdorf Porzellanfabrik. Brady, *Electrician*, vol. 61, pp. 322, 1908, Messrs. Bullers, Ltd.

‡ *Journal of the Institution of Electrical Engineers*, vol. 45, p. 685, 1910. *Electrician*, vol. 55, p. 809, 1905.

of Electrical Engineers. Those who have worked with the gap specified know that it is difficult to check the American values and even to repeat their own results on successive days. The reason for this lies in the effects on the brush discharge of humidity, pressure, and temperature, position of the needles with respect to the supports and neighbouring objects, and the local conditions of the circuit. The brush discharge in the case of needle-points always precedes the spark (excepting at very small distances). A screening by metallic discs * at the back of the needles will not prevent humidity, pressure and temperature destroying the prestige of the "standard" gap. The author uses spheres, the diameters being chosen so that no brush discharge, or rather no glow, shall be observed at the sparking voltage. Thus all sparking voltages are below the uncertain kink stage † in spark-distance curves, the kink being due to the formation of the brush discharge. The effect of humidity is eliminated. The effect of temperature can be corrected—the spark potential varying inversely as the absolute temperature. Variations in atmospheric pressure affect the spark potential less before the brush stage than after. Weicker gives the corrections for spark potentials for a 10 mm. variation in pressure from 735 mm. as 1·36 per cent. Up to 70 k.v. (R.M.S. values) 2 cm. diameter spheres are suitable, to 125 k.v. 5 cm., and to 200 k.v. 10 cm.

The spark-gap method of measuring voltage is desirable where the regulation is effected by a resistance in the primary circuit which is apt to cause distortion of wave-form. The spark voltage is determined by the maximum, and not by the R.M.S. value, so that dividing the results obtained with the spark-gap by $\sqrt{2}$, the equivalent R.M.S. sine volts are obtained. In works where a large number of insulators is being tested simultaneously, and a capacity of transformer available is low, measurement should be made on the secondary side. For a small number and a sufficient capacity of transformer the ratio method can be adopted.

Puncture Tests.—The puncture test is the routine factory test applied to each shell, and the completed multi-piece insulator, to ensure against faults. The shells are tested by inverting and filling with water the unglazed parts where the cement is to be attached to the groove of the neck of the head-piece, and to the bolt-hole in the case of the pin shed. Connections are made to the water inside by brass chains hanging from rods overhead. As it is convenient to shut off the pressure in order to disconnect a punctured shell, one firm ‡ employs a small solenoid to each chain, which is released on puncture. Some of the works test the multi-piece insulator before the cement has set, so that a shell breaking down may be replaced; and others test the complete insulator after the cement has set. In a testing-room at the Locke Company's works as many as 1,000 pieces can be tested simultaneously.

* Fisher, Electrical Congress, St. Louis, vol. 2, p. 294, 1904.
† See author's contribution to the discussion on a paper by E. A. Watson, *Journal of the Institution of Electrical Engineers*, vol. 43, p. 140, 1909.
‡ *Electrician*, vol. 62, p. 717, 1908.

Each shell of a large multi-piece pin insulator is designed to have a flash-over voltage equal to the line pressure, the assumption being that it may be subjected to full potential. In the case of a smaller insulator the shells are made to flash-over at nearly twice the line pressure. In general the testing pressure is adjusted to almost the flash-over voltage for each shell and for the complete insulator. The whole insulator cannot of course be tested by a voltage equal to the sum total of the testing pressures of the individual shells, as this will be much in excess of the flash-over voltage. An example or two will illustrate this point. A 30-k.v. two-piece insulator would have a dry flash-over of 85 k.v. and wet 65 k.v. The pin shell would be tested with about 40 k.v., and the head-piece 45 k.v., these being approximately their flash-over voltages. For a 60-k.v. two-piece insulator (flash-over dry 140 k.v., wet 115 k.v.) the above shells will be tested with 60 and 80 k.v. respectively. In a three-piece insulator for the same voltage, the shells are each tested with 60 k.v.

Suspension units, except the interlink type, are tested in the same manner as the pin insulator. The units of the interlink type are each tested between the tie-wires.

There seems to be no uniformity in the duration of test chosen by different firms. In America one minute is chosen, and at one of the German works two hours! At Hermsdorf 15 minutes are taken, but if a puncture occurs the pressure is applied for another 15 minutes, and so on. There is no doubt that one minute is too short. A total duration of one half-hour is quite ample to eliminate the defective shells. A further test when the parts are cemented ensures the elimination of faulty shells.

To determine the puncturing voltage of the insulator, it should be tested under oil. One of the guarantee tests—the dry flash-over voltage—should be made on one of the samples of a batch supported on the pin and (if possible) on the cross-arm, as used under service conditions. The practice of screwing the pin direct into the porcelain leads frequently to breakage of the screw-threads if not of the pin shell. This may be avoided by wrapping the screw-end of the pin with hemp or cementing with Portland cement. An effective practice is to use a lead or malleable iron thimble cemented to the porcelain and threaded to receive the pin. The pin must not be screwed well home, but a small turn-back should be given to allow for expansion, especially for insulators in tropical countries. In the absence of a cross-arm of the exact size as in practice, a bar 2 in. wide will suffice. The bottom shed of the insulator must be at a height above the cross-arm at least equal to its radius. A half-inch solid conductor attached to the side groove with a coiled spring or with a pair of tongs (see Fig. 43) gives the dry test for insulators on corner and dead-end towers. Fixing the conductor on the top groove as ordinarily attached gives a higher flash-over voltage for the insulator. Suspension insulators are tested with the top unit suspended from the cross-arm and the half-inch conductor fixed in the clamp of the lowest unit.

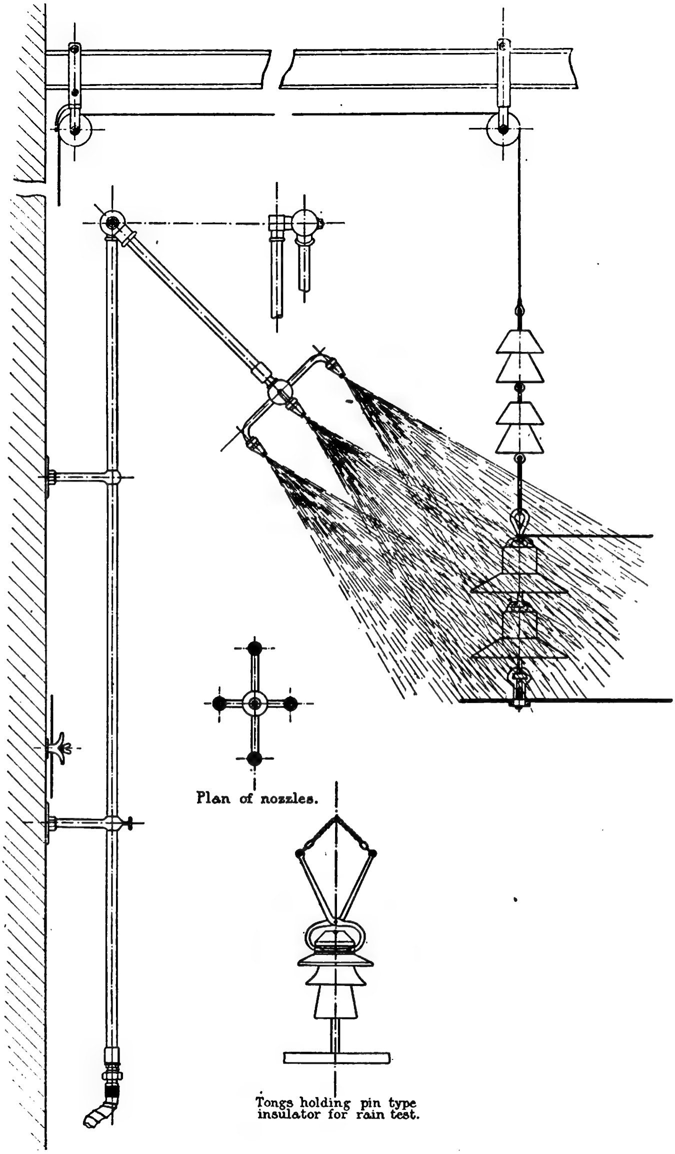

FIG. 43.—Artificial Rain Apparatus at the School of Technology, Manchester.

The voltage at which the pilot spark occurs constitutes the flash-over voltage. The humidity, pressure, and temperature should be recorded for each insulator test. This will enable the testing engineer of the insulator works to state the flash-over voltage of insulators for such different localities as a dry and cold mountainous region and a moist and warm plain. The results on page 247 offer some guidance.

Testing under Artificial Rain.—To study the behaviour and to obtain the flash-over voltage of an insulator under rain conditions in a test-room a spray apparatus is employed. This takes various forms, but unless the spray is fine, the rate of precipitation, the pressure of water, the distance and height of the nozzle, and the time element be duly considered, errors in the flash-over voltage as great as 25 per cent. may be introduced. In a large room a spray which is allowed to fall in a parabolic path gives the most accurate imitation of rain, the inclination of the falling drops being adjusted by tilting the nozzles.

The arrangement at the School of Technology is shown in

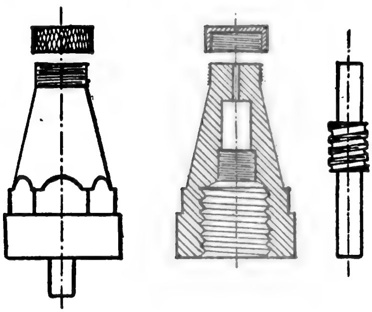

FIG. 44.—Spray Nozzle of the Artificial Rain Apparatus.

Fig. 43, consists of a set of four nozzles grouped in diamond form, the centre of which is attached to a movable arm. This arm is 2 ft. long, and is hinged to a vertical pipe attached to the wall by means of stays. The arm can be swung in a vertical plane and the pipe can be revolved through 180° in the stays, and also lifted about 3 ft. The spray can thus be controlled as regards height and direction. The nozzle, Fig. 44, consists of an outer conical shell into which fits a specially constructed screw with two threads. One is the ordinary metal thread for screwing the pin into the shell, and the other is to put a spin on the water as it passes through. The water is baffled in the orifice of the nozzle, and is split up into a fine spray, which can be altered as regards amount of precipitation and character by adjusting the centre screw. By screwing the latter right home it beds on a shoulder and stops the supply of water. The author prefers to control the precipitation by altering the pressure of the water (recorded by a gauge) and shutting off any jet by a cap provided with rubber washer, having previously determined the best position

for the nozzle screw. To calibrate the apparatus for various water pressures, number of jets working and distance of insulator from the nozzles to give a rainfall of $\frac{1}{5}$ in. per minute, an 8-in. diameter rain-gauge was substituted for the insulator.

Standard Precipitation.—The greatest rainfall ever recorded in this country was 0·3 in. per minute, in Spain 0·4 in.* The Manchester † drizzle is about 0·0001 in. per minute, and the average rains give 0·004 in., and the normal maximum for heavy storms in this country is about 0·16 in. If 0·2 in. per minute be chosen, this will amply cover the normal maximum obtaining.

The flash-over voltage is not reduced much with (vertical) precipitations greater than $\frac{1}{5}$ in. per minute, but within this value the differences in the flash-over voltages are naturally great. This can be seen from the following table :—

TABLE VI.

Line Voltage. (Kilovolts.)	Dry Test. (Kilovolts.)	Rainfall (Vertical) per Minute.		
		0·004 in.	0·5 in.	1 in.
11	55	42	35	34·5
35	96	79	70	68·0
50	124	100	88	85·0

The direction of the spray influences the wet test, with greater inclinations a wider area of the surfaces becomes wet. From actual tests an angle of 45° gives a mean result, and it is about the direction of rain in a strong wind. The standard precipitation in England and America is $\frac{1}{5}$ in. per minute, and in Germany 4 mm. at an angle of 45°. It is incorrect to incline the insulator at 45° and have the spray falling vertically on it. A false value of the flash-over voltage is obtained on account of the water running away in a stream on one side.

To prevent too much splashing, due to the pressure of the water and giving low readings, the minimum distance employed by the author is 5 ft. from the nozzle to the vertical line passing through the centre of the insulator; the tap pressure of water employed is 40 lbs. per square inch. The time element is also very important. No readings should be taken at less than 15 minutes. The humidity, temperature, and pressure should be duly recorded.

To compare the relative merits of two types of insulators Weicker suggests that the first brush discharge occurring in damp atmosphere either between sheds or the pin shed and the pin, shall be the criterion between the types, which otherwise give the same mechanical and

* Hann, *Lehrbuch der Meteorologie*, pp. 272, 273. Hellman, *Die Niederschläge in der Norddeutschen Stromgebieten*, p. 146.

† Maximum rate recorded at Godlee Observatory was 0·06 in. per minute. August 16, 1909.

electrical characteristics. In misty weather such a discharge would constitute a loss. The atmosphere surrounding the insulator can be made damp by the use of steam.

Insulators under Natural Weather Conditions.—It is difficult to study the behaviour of insulators by imitating in a test-room such weather conditions as snow, hoar-frost, sleet, etc. Recourse must be had to actual experience on a transmission line or to a laboratory in the open, as at Pankow, Berlin,* and at Hermsdorf.† The effects of smoke and dirt on prolonged exposure, the comparison of different types of insulators supported as in actual operating conditions under the same weather circumstances, etc., can thus be effectively studied. A heavy wind will diminish the ionisation and cause an increase of the flash-over voltage by a small percentage, but rain accompanying a strong wind starts the initial brush discharges earlier and gives a wet flash-over voltage less than that for no wind.

A large fan was arranged in the school test-room to imitate the effects of a heavy wind. The dry flash-over voltages for an insulator with and without the fan blowing were 75 and 73 k.v. respectively. Rendering the air humid by steam and fixing the insulator over a tank into which water was sprayed, a flash-over test—with the fan working —gave 59 k.v. The standard precipitation test required 50 k.v.

Water in the frozen state, as hoar-frost, icicles, and snow, is a fair insulator.‡ So long as the deposit of hoar-frost on the outside surfaces of the sheds is small the insulation is good, and a pressure applied quickly would give a flash-over voltage not far removed from the dry test value. But if applied slowly, the deposit melts and a lower value results. With a heavy deposit of hoar-frost on all surfaces the leakage is not much greater than with a mist or fog.

Snow falling at a temperature below freezing-point will generally form a cap on the head-piece of the pin insulator and on the topmost unit of the suspension type. The flash-over voltage is unaffected. Photographs of the flash-over sometimes show the sparks passing outside, and at other times under the snow cap; in the case of the latter each spark furrows a path to the wire. If large snow-flakes are driven on to the sheds or other units of the suspension type, and in freezing form a crust, as in Fig. 45, the sparks behave in the same manner. Driven snow falling at a temperature above freezing-point forms a thawing mass between the sheds or units, and we then have the severest conditions with which an insulator meets. Brush discharges (and even surface sparks) can take place at the line pressure. Table VII.§ indicates the leakage loss of an insulator for a line voltage of 6,500 volts under various outside weather conditions. The last item shows an important condition which is not covered by the laboratory test at normal precipitation.

* *Electrical World*, vol. 48, p. 74, 1906.
† *Electrician*, vol. 62, p. 717, 1908.
‡ Weicker, Dissertation, Dresden, 1910.
§ Weicker, *Elektrotechnische Zeitschrift*, vol. 31, p. 744, 1910.

Icicles below freezing-point are as good insulators as snow. An insulator covered with icicles tested for flash-over will show many of the sparks passing adjacent to a long icicle (see Fig. 46), but as melting soon sets in the sparks emerge from their ends at a lower pressure.

The behaviour of sooty and soiled insulators depends upon the state of the weather. The author has obtained scarcely any difference in the dry flash-over voltages in most severely soot-blackened and dirty insulators, and only a small difference in the voltage at which the initial discharges commence. In Fig. 47 A two similar insulators, one clean and the other soot-blackened, are shown flashing over at the same voltage (93 k.v.) The characters of the initial surface discharges are somewhat different; on the clean insulator they are bluish, and on the other reddish with white spots. On a damp day the soot or dirt will attract moisture, which tends to lower the insulation resistance and to start the initial surface discharges with ultimate flash-over earlier than

TABLE VII.

Weather Conditions.	Measurements taken on 300 Insulators.	Calculated for 1 Insulator.
Dry	15 watts (about)	0·05 watt
Fine mist	46 „ „	0·15 „
Fall of snow below 0° C. ...	70 „ „	0·25 „
Heavy rain	300 watts (maximum)	1·00 „
Continued drizzle with 100 per cent. humidity ...	320 watts	1·10 „
Stormy wind and very heavy downpour	450 „	1·50 „
Heavy sleet with strong driving wind	650 „	2·20 „

for a clean insulator. Fig. 47 B shows the behaviour of the same insulators of Fig. 47 A with moisture condensed on the surfaces. With the pressure brought up quickly flash-over occurred at 50 k.v. Experiments* conducted in Switzerland on insulators of various patterns of normal working voltages ranging from 3,000 (Simplon Tunnel) to 25,000 (Bexneau-Lontsch), blackened under severe conditions, indicate a lowering in the flash-over voltage of 10 per cent. in the dry state and 15 per cent. under the rain test. From a large number of insulators exposed for a number of years to the smoke and dust of a porcelain works, measurements of leakage loss indicate that for clean insulators it is half that of soiled ones. It has been observed that the leakage current over the surfaces attracts soot and dust, especially to the strong parts of the electric field. This attraction for smoke must be duly considered in lines which cross, or are near, steam railways.

The conditions near a sea-coast with its salt fogs are more severe

* *Schweizer Electrotechnischer Verein, Bulletin*, I. pp. 160–167, 1910.

than for an insulator in dry mountainous regions. The salt, perhaps mixed with dust, encrusts the sheds and, becoming damp, offers an easy path for discharges. Chemical works adjacent to the line may also produce trouble. In the case of a 50-k.v. transmission line in Norway, near some carbide works, the heavy brush discharges between the bolt and the bottom shed necessitate a periodic cleaning once a month. The suspension type has the advantage of being cleansed by rain and wind in a better manner than the pin type, and for such localities provides considerably less leakage.

In conclusion, the author desires to express his thanks to Principal Reynolds and the School Committee for the facilities afforded for carrying out the experimental part of the paper; to the following manufacturers for their co-operation in supplying insulators and other porcelain pieces: Messrs. Taylor, Tunnicliffe & Co., Messrs. Bullers, Ltd., and Messrs. the Hermsdorf Works. The author is most grateful to Dr. Weicker (Chief Electrical Engineer of the Hermsdorf Works) for his kind interest and assistance in supplying valuable information and some of the photographs—those under snow and ice conditions are his.

The author is indebted to his colleague, Mr. R. B. Fishenden, for the photographs taken at the school, and to his research assistant Mr. R. B. Breeze, for drawings and experimental help.

APPENDIX.

Potential Gradient and Density of Electric Charge.

(*a*) *Case of Capacity with a Dielectric between Electrodes.*—From the definition of potential, the strength of field H, in any medium, is equal to the potential gradient, viz.:—

$$H = -\frac{dV}{dx}.$$

In a medium of dielectric constant k, a flux density B will be produced such that—

$$B = k\,H \quad \text{(in air } B = H\text{)}.$$

The electric charge per unit area σ associated with a flux density B is given by—

$$B = 4\,\pi\,\sigma;$$

hence—

$$H = \frac{4\,\pi\,\sigma}{k},$$

or—

$$\sigma = \frac{k}{4\,\pi}\,.\,H = -\frac{k}{4\,\pi}\,.\,\frac{dV}{dx}$$

The density of the charge is thus proportional to the potential gradient and the dielectric constant. Taking k for electrical porcelain as about 5, for a given potential gradient, σ is five times that with an air medium.

A breakdown of air between two parallel plate electrodes, or rather between very large spheres, takes place when the potential gradient is about 30 k.v. per centimetre.* With suitable distance between the electrodes a glow is established ; then the conducting zone alters the equipotential surface, and further increase of voltage promotes the brush discharge, and finally the spark and the arc.† For small distances the glow and the spark are simultaneous—the former cannot be discerned.

With porcelain between the parallel plate electrodes the potential gradient is $\frac{V}{d}$, where V is the difference of potential (maximum value of alternating current) between the plates and d is the thickness of the porcelain plate. The flux density B in the porcelain is $\frac{kV}{d}$, viz., $\frac{5V}{d}$ This will be the approximate value of the flux density at the edge of the electrode—in air. Hence, when the flux density gives a potential of 30 k.v. per centimetre, a glow appears on the electrodes, when—

$$\frac{5V}{d} = 30.$$

For a thickness of 1 cm., $V = 6$ k.v. (maximum) or 4·5 k.v. (R.M.S.) starts the glow. With increasing pressure the glow or corona is extended and becomes the surface brush or streamer. On account of the conducting (ionised) air, the areas of the electrodes are hereby increased. (Since the total quantity of electricity produced by unit difference of potential is a measure of the capacity, the extended area of the electrodes producing a greater total charge is equivalent to an increased capacity—see footnote, page 265). The density of the charge is greatest at the edge of the metal electrodes, and is diminished at the limit of the streamers. The large densities lead to surface sparks, which initially are reddish but become of vivid whiteness as the quantity of electricity increases (provided the energy of the source of supply is great enough). At the ends of the surface sparks there are less densities of charge, and also less potential gradients, than at the metal electrodes ; as the pressure is increased, the rate at which the sparks lengthen is very great. The spark-length varies as the cube to fourth power of the pressure. Fig. 48 shows the surface sparks bridging two electrodes on either side of a sheet of glass. Thus a large capacity and a high potential gradient produce the surface sparks (see pages 246 and 265).

* *Journal of the Institution of Electrical Engineers*, vol. 43, p. 143, 1909.

† The various forms of electric discharge have been discussed in a paper by Cramp and Hoyle (*Journal of the Institution of Electrical Engineers*, vol. 42, p. 297, 1909). The arc may be prevented from forming (as in the majority of the photographs in the paper) by limiting the energy of the supply, viz., by inserting a resistance in the primary of the transformer.

The relation of distance between two electrodes and spark voltage is linear when the spark is promoted by a brush discharge—that is, when the conditions are past the kink stage in the curves II. and III. of Fig. 14; but when by a large capacity it becomes a "surface spark," the relation is then cubic.

(*b*) *Case of Capacity with a Compound Dielectric*—i.e., *Porcelain and Air between Electrodes.*—In Fig. 49 A and B are two plate electrodes at a distance d apart at potential V and zero respectively. The potential gradient or field strength $H = \frac{V}{d}$ for any medium filling the space between A and B—*i.e.*, whether porcelain or air. Obviously the greater the value of d the smaller will be the potential gradient. Now suppose the space is made up of porcelain of thickness d_1 and air of thickness d_2 where $d_2 = d - d_1$.

Let V' = the potential of surface of separation C. The tubes of force will be perpendicular to the surfaces A, B, and C (neglecting the

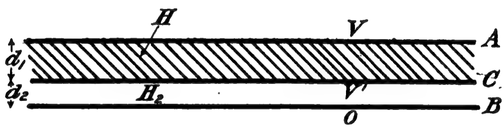

FIG. 49.—Compound Dielectric between Parallel Planes.

fringing at the ends or assuming very large diameter spheres instead of plates). The field strengths H_1 and H_2 are given by—

$$H_1 = \frac{V - V'}{d_1} \quad \text{and} \quad H_2 = \frac{V'}{d_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The flux densities are equal—

$$B_1 = k\,H_1 \quad \text{and} \quad B_2 = H_2.$$

$$k\,H_1 = H_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

From (1)—

$$H_1 d_1 + H_2 d_2 = V,$$

combining with (2)—

$$H_2 = \frac{V}{\frac{d_1}{k} + d_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$H_1 = \frac{V}{d_1 + k\,d_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Before the introduction of the porcelain plate—

$$H = \frac{V}{d} = \frac{V}{d_1 + d_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Hence $H_2 > H$—that is, the potential gradient in the air-gap has

increased. When the thickness of the air-gap is comparatively small, the value of H_2 approximates to k H. If the potential gradient before introduction of the porcelain was slightly less than 30 k.v. per centimetre, breakdown of the air-gap takes place after introducing the porcelain.

If instead of one, two sheets of porcelain be taken, each $\frac{d_1}{2}$ thick, and placed contiguous to the electrodes, equation (3) still holds. In fact, if n sheets of total thickness d_1 be chosen, discharges take place in the air-gaps when the gradient exceeds 30 k.v. per centimetre. This is the manner in which the narrow air-gaps between porcelain sheds of line insulators break down.

Combining (3) and (5)—

$$H_2 = \frac{k\,d}{d + d_2(k-1)} \cdot H \quad . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

By making d_2—the thickness of the air-gap—as large as possible H_2 becomes equal to H. Simultaneously the gradient in the porcelain sheet is also reduced, since—

$$H_1 = \frac{H_2}{k},$$

or—

$$H_1 = \frac{d}{k\,d - d_1(k-1)} \cdot H \quad . \; . \; . \; . \; . \; . \; . \; . \quad (7)$$

From equations (6) and (7) we have—

$$H_2 > H > H_1.$$

A numerical example will illustrate :—

Let—

$$d = 2 \text{ cm.} \quad V = 60 \text{ k.v.,} \quad \text{and} \quad d_1 = 0{\cdot}5 \text{ cm.}$$

Therefore—

$$d_2 = 1{\cdot}5 \text{ cm.} \quad \text{and} \quad V \text{ in C.G.S. units} = 200.$$

$$H_2 = \frac{200}{\frac{0{\cdot}5}{6} + 1{\cdot}5} = \frac{200}{1{\cdot}51} = 132 \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

$$H_1 = \frac{200}{0{\cdot}5 + 6 \times 1{\cdot}5} = \frac{200}{8} = 25 \quad . \; . \; . \; . \; . \; . \quad (4)$$

$$H = \frac{200}{0{\cdot}5 + 1{\cdot}5} = \frac{200}{2} = 100 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

The potential gradients for the H_2, H_1, and H are 40, 7·5, and 30 k.v. per centimetre respectively. When a brush discharge bridges the air-gap the gradient on the porcelain will be approximately—

$$\frac{V}{d_1} = \frac{60}{0 \cdot 5} = 120 \text{ volts per centimetre.}$$

The relation of the densities σ_1, σ_2, and σ is—

$$\sigma_1 = \sigma_2 = \frac{k\,d}{d + d_2 (k - 1)} \cdot \sigma.$$

To summarise the above, suppose we have a porcelain wedge of such diminishing thickness between the electrodes that the diminution in flux density is very gradual; then the potential gradient in the air-gap diminishes from 5 H to H, and the densities of electric charge from 5σ to σ. The corresponding quantities in the porcelain diminish from H to $\frac{1}{5}$ H and 5σ to σ. Where the air-gap breaks down, the gradient on the porcelain is greater than H.

With unequal electrodes instead of parallel plates the divergence between H_1 and H_2 is greater. An air-gap near the electrode of large curvature will have a less potential gradient than when near the other electrode.

Discussion.

Professor E. W. Marchant: One of the best ways of investigating the distribution of stress in the material of an insulator would be by using a modification of the stream-line apparatus developed by Professor Hele-Shaw and others. It should be quite easy to determine the stress accurately by this means, the circular shape of the insulator being taken into account by varying the thickness of the film through which the liquid employed in the stream-line experiment had to pass. The same apparatus might be used with great advantage to investigate the stress in the experiments described with the tilting plates as shown in Fig. 4. The results given as to the breakdown voltage between two wires wound on a porcelain cylinder are very remarkable, but the cube law stated by Mr. Lustgarten is open to some criticism. If in the experiments the wires had been increased in diameter in proportion to the distance between them, and the cylinder on which they were wound also in the same proportion, a linear law between the voltage and the breakdown distance should have been obtained. The reason why the cube law appears to have resulted from these tests is that when we get high voltages on the wires a corona forms round them which gives rise to a ring of surface sparks on the porcelain, and the actual distance between which the breakdown spark has to take place is much less than the distance between the wires. The linear law is borne out by the dimensions of the insulators which are manufactured, since the weight of an insulator is proportional to the cube of its linear dimensions, and the author's figures show that the weight of an insulator is Professor Marchant.

Professor Marchant.

approximately proportional to the cube of the voltage at which it has to work. The results with the "metal shed" insulators are very interesting. The metal shed would appear to have much the same function as the metal sheath which is sometimes put between the layers of insulation in a graded cable, that is, it tends to equalise the dielectric stress through the insulation. I should like to ask if the author could give any information as to where the remarkable rainfall of 0·3 in. per minute occurred; the average rate of rainfall in a very severe storm must be less than this. A tropical storm in which 3 in. of rain fell in 10 minutes would be one of quite exceptional severity.

Mr. Burton.

Mr. J. BURTON: The most interesting factor in the author's paper so far as I am concerned is the point that he has made with regard to design. This seems to be one of those things which we English manufacturers have more or less overlooked, and it is a point with regard to which the Continental makers have certainly stepped in advance of us. It is often assumed, of course, that porcelain is a very much better dielectric material than the stoneware made in this country, but according to the author's paper that is only slightly so; the puncture value of porcelain is only slightly higher than that of the English ware. The nature of the English body enables our insulators to be made in one piece on the thrower's wheel, and not in moulds, and this makes them a much more compact and solid article; it also enables the finished article to withstand a greater tensile strain than is the case with porcelain. The English ware is not so brittle; it is a little stronger, and its puncture value is not quite so high. I think the author has made it very clear that the design of the insulator is a very much more important point than the material of which the insulator is made—of course within certain limits—and from that point of view his paper will be most valuable, not only to electrical engineers but also to manufacturers in England who have to make these insulators.

Mr. Symons.

Mr. H. D. SYMONS: The photographs which the author has included in his paper must have taken a considerable amount of time and trouble. Surface discharges and arcing over porcelain insulators under surface conditions are, however, much more severe than those shown in the photographs which were taken with a testing transformer. The author calls attention to the wide difference of opinion as to how long-voltage tests on porcelain insulators should be maintained, and recommends a 30-minute test. For porcelain manufacturers with a test-room equipped to test many insulators at once this would be quite satisfactory. For the electrical manufacturer, however, I consider that a voltage test of 2½ to 3 times normal working voltage, maintained for 5 minutes, is a fair and satisfactory one for discovering faulty insulators. If at the end of this time any rise in temperature has taken place on any insulator it should be continued for half an hour. I endorse the author's recommendation that puncture tests on porcelains should be conducted under oil, for only under such conditions is it possible to obtain an accurate and reliable value for the dielectric strength. With reference to Mr. Burton's remarks with regard to the difference between

the English and German porcelain, it has been my experience that on the whole the English porcelain is superior from an electrical point to the German material. The dielectric strength of the English porcelain is generally a little higher, and the material is tougher and more free from air bubbles than the German porcelain. With regard to the tests on soot-blackened insulators, I would like to ask the author whether he has made any long-time voltage tests on insulators under such conditions. Any discharge or flash-over tests that are made with dirty insulators depend so much on the dirt that is used that it is not safe to assume that the flash-over voltage is not appreciably reduced by the accumulation of dirt on the insulator. The condition of this dirt and its ingredients enormously affect the result, and often the difference is only apparent on long-time high-voltage tests. Mr. Symons.

Mr. MILES WALKER: While Professor Marchant is right from his point of view in what he says about the increase of the insulator in the same proportion in all three dimensions, I do not think his remarks quite cover the author's point. As I understand the matter, the ordinary petticoat insulator, particularly in the large sizes, resembles somewhat the tube of insulation surrounding a central pin analogous to that illustrated by the author in his diagram. If the cube law holds for the tube, the same law affects the insulator so far as its length is concerned. The addition of wide collars will interfere with that cube law, and if the collars are wide enough we get the conditions contemplated by Professor Marchant. Some speakers have regarded this subject as affecting us only so far as our export trade is concerned. That may be true at the present time. We have been very backward in this country in extra-high-voltage work. But I do not think that it will always be so. We have made a big advance when we have here on the table of our Manchester section this fine array of high-voltage insulators, and when we see how well they stand up to their work under the very heaviest precipitation of rain. Certainly there is nothing in our climate that is going to prevent us using 100,000 volts. Our difficulty is in "way-leaves." But in these days of progress that will not be for long a difficulty. I think that before many years are gone we shall see much larger transmission schemes carried out in this country than we have had in the past, and then the subject matter of this paper will be of vital importance to us. Mr. Walker.

Mr. W. POLLARD DIGBY: I am a little in doubt as to the value of the author's artificial rain-water test. The author's experiments have been conducted presumably with Manchester tap-water, which is a very pure liquid, probably far purer than Manchester rain-water. The author's commercial tests are both excellent and practical, but I would like an expression of his opinion as to the ratio between the working voltage on the transmission line and the test pressure at the factory. The note on page 274 in regard to sooty insulators, which in a dry condition are practically as good as clean insulators, offers an interesting parallel to the case of dry switch oils, which have practically the same dielectric strength when black through suspended carbon as when Mr. Digby.

Mr. Digby. newly received. The author's remarks as to ice on insulators are an interesting proof of a deduction of Mr. Sidney Evershed's. Mr. Evershed, from a study of the temperature coefficient of specific resistance of distilled water, came to the conclusion that ice must be an insulator, water only becoming a partial conductor as the ice melts. The author's striking experiments prove the soundness of Mr. Evershed's deductions.

Mr. Mallinson. Mr. A. B. MALLINSON: The author makes clear the necessity for the angle on the shed, but it would be interesting to know whether in the course of these investigations any comparisons have been made which would show the relative advantages of insulators with concave, convex, and straight sheds. One of the first things which impresses one when proceeding to install a high-pressure line is the great variety of insulators offered, each type being claimed by its maker to be better than any other. An unbiassed comparison of the various types would therefore be of interest. Another point in the paper which I would refer to is what might be termed the "atmospheric factor." I do not think that in the paper the author has given this factor the prominence it in practice has on the selection of the insulator. I have found by actual experience in this country that it is necessary to multiply what the manufacturer tells us by about four to get an insulator which is really satisfactory. It is not that I have had any flashing over on them, but that when fixed on the line in a manufacturing or colliery district we get such a poor insulation test that it is not possible for the engineer in charge to get a true idea of the state of his equipment without isolating the line and individually testing the sections of the equipment. For instance, at a colliery working at 2,500 volts the insulators supplied by the maker for a 5,000-volt line were quite useless, as unless they were cleaned every month or so it was impossible to get an insulation test of more than about 0·1 megohm on a line only ¼ mile in length. With reference to high-pressure lines in this country, I notice that mention is made of one at 10,000 volts in Cornwall. I might call attention to the fact a line is now being erected in North Staffordshire to work at 12,000 volts, and so designed that eventually the pressure can be put up to 25,000 volts.

Mr. Frith. Mr. J. FRITH: To me the theoretical part of this paper is really the most interesting, in that it would be of assistance in the design of new insulators, making for economy of material and space, and ensuring that all the parts of the insulators are equally strong. I think that some confusion may arise from the rather indiscriminate use of the three terms: "potential gradient," "flux density," and "intensity of electrostatic field."

Mr. Cunliffe. Mr. R. G. CUNLIFFE: I think many engineers who have used porcelain insulators will appreciate the difference between moulded and "disc spun" insulators. It has been my experience that moulded insulators break, owing to internal stresses, under the action of very slight shock. The unstable "kink" or brush discharge stage shown in the curve No. III. of Fig. 14 appears to depend partly on the dimensions of the electrodes. I have experienced effects similar to a

heavy brush discharge in air with direct current at as low a pressure as 200 volts. The case in point occurs between the two lead plates of a water resistance in which the solution consists of ordinary soda dissolved in water. The withdrawal of the plates is followed by evaporation of the solution with resulting crystallisation of soda on the surfaces of the plates, and on the plates being next lowered into the solution bright bluish sparks appear on the adjacent sides of the plates. The phenomenon is attended by a loud crackling sound, but there is no arc or spark bridging the space between the plates. I agree with Mr. Digby that there are objections to artificial rain-water tests, as I have found great variations in specific resistance between different samples of tap-water. The water used by the author, obtained from the Manchester Corporation mains, was soft Thirlmere water of very high specific resistance. As regards the author's view that a coating of soot or carbon on the surface of an insulator will not have any effect in dry weather, I am in agreement with him, but think that in wet weather the effect of such a conducting coating will be to give the insulator the properties of a "metal shed" insulator. **Mr. Cunliffe.**

Mr. A. TEIXEIRA: I notice on page 266 it is stated that "the metal shed units in Fig. 37 do not ensure the arc passing from metal to metal." It ought to be "from metal shed to metal shed." Some photographs which I took in the high-tension room of the Manchester School of Technology show clearly that the arc started from the bolt to the metal shed in each insulator, and not from metal shed to metal shed. This is due to the fact that the distance between the metal sheds was very great—about 11 in. The pressure was 102 kilovolts. The arc would pass from metal shed to metal shed if the sheds were very near together, as in the case of the sunken insulators (Fig. 38). **Mr. Teixeira.**

Mr. WM. CRAMP: It occurs to me that some sort of proof should be given by the author of the cube law, or the "fourth power" law. It is not sufficient to say that a relationship is apparently cubic, but some proof, or at least some probable reason, should be given to explain why it is so; or failing this, a definite statement should be made that there is apparently no explanation. I think the author has really done the electrical and porcelain industries a great service by calling their attention to the fact that the surface leakage which we have all been taught to avoid is not really important, if the question of capacity is looked after properly. This point cannot be too often emphasised. **Mr. Cramp.**

Professor W. W. HALDANE GEE (*communicated*): The curve of leakage loss of the 13-k.w. insulator in a mist, to which 26 kilovolts is applied (shown in Fig. 16) reminds me of curves showing the drying effect of electrical endosmose, but the phenomena with alternating-current pressure are simpler and should be more easily explained. The power P spent on the surface of the insulator at any instant is E^2/R, where E is the applied constant pressure and R is the resistance of the film of moisture. As the film evaporates, owing to electric heating, R will increase, and the rate of increase will depend on the electrical energy spent on the film. I find that log P^2t approximates **Professor Gee.**

Professor Gee.

to a constant. Here t is the observed time, and P can be obtained from the curve by deducting the loss due to conductivity, etc. Below are shown the results of applying the above expression to a number of points on the curve :—

P.	t.	log $P^2 t$.
12·10	0·5	1·86
8·80	1·0	1·89
6·80	1·5	1·84
5·60	2·0	1·80
4·80	2·5	1·76
4·20	3·0	1·72
3·40	4·0	1·67
2·80	5·0	1·59
2·55	6·0	1·59
2·30	7·0	1·57
2·15	9·0	1·62
1·95	10·0	1·58

The values of log $P^2 t$ are in fair agreement for the points taken on the parts of the curve that are more likely to be less affected by observational errors and other causes.

Mr. Breeze.

Mr. R. B. Breeze (*communicated*) : With regard to the interlink suspension insulators shown in Figs. 26 to 30 and in Fig. 41, I should like first of all to fully endorse all that the author has said concerning this type. I have tested several, and have found them very liable to puncture between the links. A 6-in. Hewlett type similar to that shown in Fig. 41 has punctured, not between the tie-wires, but through the porcelain on the top. I also wish to mention that the flux will be better distributed under rain than when dry, as in this case the top hole for the link will be filled with water, and so will act as if it were a solid conductor filling the hole and having a greater area. As the distance between the units in this type is very great and the electrostatic field in the units is so very strong between the tie-wires (due to the large quantity of porcelain and the small electrodes), the flash-over will take place from tie-wire to tie-wire over each unit, instead of over the whole series ; this is very liable to cause fracture of the units. Another point is that, owing to this great distance apart, the insulators are very effectually cleansed by rain.

Mr. Lustgarten.

Mr. Lustgarten (*in reply*) : I think Dr. Marchant's suggestion with regard to Professor Hele-Shaw's apparatus showing stream-line motion is a good one, but it would be difficult to imitate the stress in the porcelain and air, having regard to the varying thicknesses of the two media, and to their relative dielectric constants. The stream-lines from a "source" to a "sink" would show the distribution of stress in

Mr. Lustgarten.

the air between the electrodes of Fig. 3. The effect of an additional annular "sink" would imitate the tilting electrode.

With regard to Dr. Marchant's criticism, the cubic relation of spark voltage and spark distance between electrodes has only reference to the "surface spark" conditions. When, irrespective of the curvature of the electrodes and irrespective of the thickness of the dielectric, a high potential gradient and a large charge density (namely, a great dielectric constant of the medium) produce these sparks, the relation is apparently cubic (and for large spark distances is a fourth power). If flashing over is promoted by a brush discharge, then the relation is—as Dr. Marchant points out—linear. For instance, with electrodes on opposite sides of a glass plate $\frac{1}{4}$ in. thick and a spark distance of 13 in., the flash-over voltage is 58 kilovolts (surface spark condition); but with the electrodes on the same side of the glass plate and separated by the same distance (13 in.), only the brush discharge is present, the flash-over voltage being 128 kilovolts. The potential gradients at the edge of the electrodes in the two cases are very different, due to the thickness and to the constant of the dielectric between, and due to ionised air adjacent to the electrodes. The same remarks hold good with wire electrodes on a porcelain tube with and without a metal rod in its interior. An increasing diameter of tube but of a constant thickness of dielectric does not affect the relation. Increasing the thickness reduces the gradient and the charge density until, for large thicknesses, introducing the metal rod the surface spark is not produced. The corona formation on wire electrodes on porcelain tubes depends not only on their radius of curvature, but also upon the dielectric constant—that is, it depends on the potential gradient of the air at the point of contact with wire and porcelain. With small thicknesses of tube and a large diameter of wire the corona will form earlier than with large thicknesses of tube and small diameter of wire. In the former case there will be a tendency towards surface spark formation which may not obtain for the large thickness of tube. Different curvatures of electrodes in contact with the porcelain will affect but little the voltage producing the surface corona; with plate electrodes 4,000 volts start the initial glow with 1 cm. of glass plate (see page 276). Dr. Marchant's observation that the actual sparking distance with a ring of surface sparks is less than the distance between the wires might also be extended to that between the ends of the brush discharge between needle-point electrodes (curve II., Fig. 14), but the voltage-distance curve is only linear where the distance is that between the metal surfaces. Dr. Marchant quotes as evidence of the linear law that the weight of insulators manufactured is proportional to the cube of the voltage. I cannot agree with this, for if the height—see Fig. 24 (*a*)—is to vary linearly with the voltage—the diameter of the insulator remaining constant—the weight would be merely proportional to the voltage. As Dr. Marchant points out, it is interesting to note the introduction of the metal shed in insulator design, and compare its function with that of the metal in the condenser-type terminal tubes for transformers, etc.

Mr. Lustgarten.

In the latter, the metal layers reduce the stress from a logarithmic to a linear distribution. The metal shed does more: it reduces the gradient in the air contiguous to it.

On page 272 I have added the references to the exceptional rainfall rate. A very high rainfall rate may not be maintained for more than 1 minute, but the insulator must not be taken unawares—it must withstand the maximum rate and for any length of time. The opinion of an English potter on the subject is valuable. I am glad that Mr. Burton agrees with me that the method of firing of the hard Continental porcelain probably leads to a greater electrical strength than the English ware, but to the production of a more brittle article. This point will answer Mr. Symons's opposite contention. Faulty design leads to overstressing of certain parts. With proper design, such that the insulator flashes over under all circumstances, the English ware will be more desirable than the more brittle Continental porcelain.

Mr. Symons calls attention to the routine factory puncture tests. The testing pressure is slightly less than the dry flash-over voltage. With the present designs a good insulator can only be punctured under oil. As the working of a transmission line depends largely on the complete safety against puncture of an insulator, the duration of the routine factory test of the pieces and of the whole insulator should not be curtailed. Puncture of the faulty insulators becomes less as the time of test increases, but is never entirely eliminated. The reliability against puncture is therefore greater after half an hour's test than after 5 minutes. The insulator whose temperature rise is 50° C. and above should be discarded. With regard to time tests on dirty insulators, I have not conducted tests longer than one half-hour, but the results should not be very different, as the sparking over is due to a capacity effect. The Swiss experiments with insulators blackened under service conditions (page 274) gave only a reduction of 10 per cent. Salt crustations would of course make a difference.

With reference to Mr. Walker's remarks, widening the collars or sheds instead of altering the height of the insulator, to effect an increase in the spark distance, will not altogether interfere with the cube relation. A great width of the sheds and a small thickness of the porcelain between the line wire and the pin produce a large capacity; surface sparks will hence be formed. Widening the insulators approximates to the conditions of the glass plate of Fig. 48. Yet the wide pin-type insulators are better than long ones for electrical and mechanical reasons given in the paper.

In reply to Mr. Digby, artificial rain experiments with salt and distilled water gave no difference in the wet flash-over voltage. The voltage will depend on the brush discharge, as in Fig. 24B, and the potential gradients at the water-drops will not be sensibly different for salt or distilled water, especially as the leakage currents are so small. The ratio of the wet flash-over voltage to the line voltage should be about $1\frac{3}{4}$ to 3 for 10 kilovolts to 70 kilovolts respectively. The safety factor for the dry state will be about $2\frac{1}{2}$ to 5. The following table gives

Mr. Lustgarten.

the safety factors for pin-type insulators (for suspension insulators see pages 259 to 261):—

Line Pressure, *a* Kilovolts.	Flash-over Voltage.		Safety Factor.	
	Dry, *b.* Kilovolts (about).	Wet, *c.* Kilovolts (about).	Dry, Ratio *b/a*.	Wet, Ratio *c/a*.
10	50	30	5·0	3·0
20	73	50	3·6	2½
30	90	65	3·0	2¼
40	115	82	2·8	2·0
50	133	95	2·6	1·9
60	145	110	2·4	1·8
70	160	120	2·3	1·7

My experience with dry oils when black with a large amount of suspended carbon is that the dielectric strength is lowered on account of the altered flux distribution which the particles produce. When the particles fall to the bottom of the containing vessel, the dielectric strength is the same as when new oil is used. I have found a treatment consisting of flashing an oil and removing the carbon constitutes an effective means of removing the last traces of moisture and impurities, the carbon in the nascent state absorbing the latter.

In reply to Mr. Mallinson, the advantages lie with curved sheds as in Fig. 7D, but not as in Fig. 7C. The convex type is not satisfactorily cleansed by rain. Moreover, the falling drops of water are pulled inwards more readily than in the other types of Fig. 7. The other advantages are discusssd on pages 245 and 246. With regard to the "atmospheric factor," the standard precipitation test will amply cover the maximum rainfall rate which is likely to occur. In a mountainous region with severe snow conditions, for places near the sea coast or near chemical works, an insulator should be chosen to give an extra safety factor of ¼ for 70 kilovolts to ¾ for 10 kilovolts. I have indicated in the paper that the suspension type is better for such localities. The insulator quoted by Mr. Mallinson must be of the old telegraph pattern. The severe conditions at a colliery would give for such a small size and shape a low insulation resistance, but with a pressure of 2,500 volts there would be no trouble with discharges, except in misty or wet weather.

Mr. Frith objects to the indiscriminate use of the terms "potential gradient," "strength of electrostatic field," and "flux density." From the definition of difference of potential V, as the work done in carrying unit charge against the electric force acting, we have: $\delta V = - H\, dx$, or $\delta V/\delta x = - H$, and at the limit $- dV/dx = H$. That is, the potential gradient is equal to the strength of field irrespective of the dielectric constant of the medium. From the conception of Faraday's tubes or lines of induction, we have a flux

Mr. Lustgarten.

density B (viz., number per square centimetre) equal to k times the electric strength of field (viz., the number of lines of force per square centimetre). For air k is unity. Thus the three quantities referred to air have the same meaning.

I agree with Mr. Cunliffe that turned articles are always better than moulded articles. Still, the large 10-in. suspension insulators are moulded, and can be made to withstand a mechanical test of 5 tons. In the discussion on Mr. Watson's paper on "The Dielectric Strength of Compressed Air," I showed that the unstable "kink" occurred at increasing spark distances with increase of the radius of the spheres. Incidentally I pointed out that the potential gradient at which air breaks down is 30 kilovolts per centimetre for large spheres. The phenomenon quoted by Mr. Cunliffe is very interesting. The crackling sound might be due to the crystals of sodium carbonate being suddenly "cracked off" on entering into solution, especially with the heat developed. I have already replied to the objections against the use of Manchester tap-water. The metal shed protects the insulator in wet weather, and gives it the properties discussed in the paper, but in wet weather a sooty insulator has worse electrical properties than a clean one.

I am glad to have Mr. Texeira's correction. His photographs are very convincing that even "metal shed" units require to be brought near enough together to force the arc over as in Fig. 38.

I am unable to accede to Mr. Cramp's request for a proof of the cubic (or fourth power) relation for surface sparks. Mr. Cramp quite correctly points out that capacity plays the chief rôle in insulator design, and by reducing it as in the suspension series the surface spark is minimised if not entirely eliminated.

With reference to Mr. Breeze's remarks on the interlink type, I hardly think that water in the topmost hole will relieve the stress much.

Professor Gee referred to the drying effect. The drying effect is at first due to combined leakage and capacity currents, and then only to the former. The higher value of $P^2 t$ initially indicates the presence of the larger capacity currents. It is noteworthy that the surface resistance of an insulator in a mist depends also upon the voltage applied.

In conclusion, I wish to refer to the phenomenon of the "black" spark. This is a complete puzzle to the photographic physicist, inasmuch as none of the current theories of photographic action seem to be of any help in attempting to explain it. Photographs of lightning flashes sometimes have the faint branches reversed, and sometimes the main flash also, when the photographic plate has been left exposed till the second lightning flash occurred. Experiments on the photography of sparks show that if the plate be exposed for a sufficient length of time to diffused light after exposure to the spark, partial or complete photographic reversal of the latter takes place; but if exposed before exposure to the spark no reversal occurs.

A PORTABLE ELECTRICAL INSTRUMENT FOR THE DETECTION OF COMBUSTIBLE GASES AND VAPOURS IN AIR.

By LOUIS J. STEELE, Member.

(*Paper received 2nd January*, 1912; *received in final form 24th April*, 1912.)

Owing to the risks of explosion which exist on board battleships and ships of the Mercantile Marine, as well as in various industries due to the accumulation of combustible gases and vapours, there is great need of a detector which will afford a rapid, safe, and unmistakable method of testing the spaces in which these combustible gases or vapours are believed to be present, and which will form a test which does not require any special knowledge for its application. Hitherto the detection of inflammable gases and vapours was carried out either by a chemical analysis of samples of the atmosphere under observation, or, in most cases, by means of a variation of the original Davy safety lamp, in which the cap formed on the safety lamp flame formed an indication of the presence of combustible gases or vapours. These two tests are difficult of application, and require special skill and knowledge for their use. Instruments dependent on the catalytic action of the surface of platinum have been proposed in the past by various people for the detection of combustible gases. It is well known that when platinum or other metals of the platinum group are exposed to a mixture of air with certain combustible gases such as hydrogen or marsh gas, or to the vapours of other organic compounds such as alcohol, ether, the more volatile members of the paraffin series and other hydro carbons, a combination between the oxygen of the air and the hydrogen and carbon in the combustible vapours or gases takes place, and as this combination occurs chiefly at or on the surface of the metal, it thereby causes a rise in its temperature, the magnitude of this temperature rise depending upon the ratio between the amount of the combustible vapour or gas and the oxygen present.

Probably the best known instrument in which the occurrence of the temperature rise caused by the reaction between oxygen and combustible gases or vapours under the conditions described above, is made use of is that of Dr. Liveing, the details of which were published some 15 years ago; but it is believed that all detectors designed on this principle and dependent on the catalytic property of platinum for their operation, have been found to be unreliable and unsatisfactory

for two reasons: (1) The catalytic activity of platinum changed in the course of time and use and became less sensitive and less certain in its action; (2) if the atmosphere under test contains a sufficiently high percentage of combustible gas or vapour, the temperature of the catalytic platinum will become so elevated that if in the form of a wire it will fuse and put the device entirely out of action, or, if in the form of platinum black or spongy platinum, its surface becomes fused with a consequent diminution in its catalytic activity.

The portable type of detector devised by Mr. Arnold Philip and the author, although dependent on the catalytic action of heated platinum surfaces to secure the reaction between mixtures of oxygen and com-

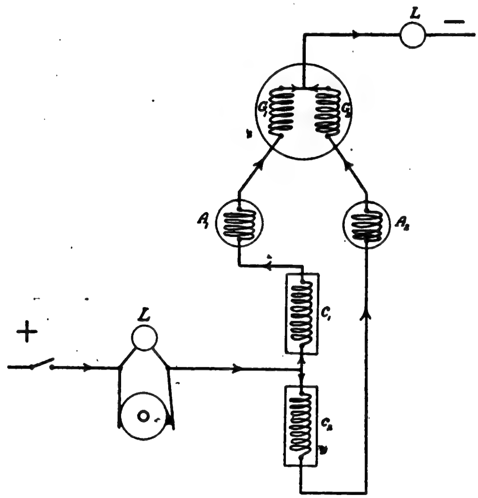

FIG. 1.

bustible organic gas or vapour which may be passed through it, is free from the above main objections relating to detectors of this class.

Observation extending over a period of more than two years on the same platinum wire coils subjected to constant testing revealed no alteration in its behaviour or resistance. The instrument, moreover, is so arranged that it is completely protected against any danger of overheating, whatever the proportion and nature of the mixture of combustible gas or vapour and air may be.

The Philip and Steele portable type of detector, the connections of which are shown diagrammatically in Fig. 1, consists of two spirals of platinum wires C_1 and C_2 of approximately the same resistance and connected in parallel. In series with each of these spirals is one of the coils of a differentially wound relay, G_1 and G_2.

The armature or relay tongue T (Fig. 2) of this relay is capable of

being moved by a very small alteration in the current flowing in either of its coils.

The two platinum spirals of the detector which are maintained at a sufficiently high temperature by the currents flowing through them are enclosed in glass tubes, and the air which is to be examined as to its contamination with or freedom from combustible gas or vapour is passed through the detector at a steady rate by means of a small hand pump on the outside of one of these tubes containing the spiral C_2, and does not come into contact with the platinum wire; the gas current then passes on to the second glass tube inside which it flows, and is thus brought directly into contact with the hot platinum spiral C_1.

In the diagram Fig. 1, the glass tubes protecting the platinum spirals, the system of pipes for passing the stream of gas through the apparatus and the casing of the instrument are not shown, but their general dis-

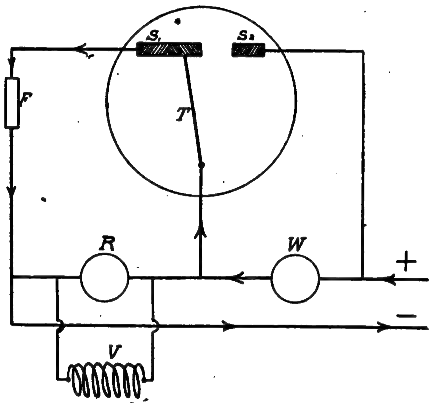

FIG. 2.

position may be clearly seen in the photograph of the actual instrument shown in Fig. 3. Fig. 3 shows the instrument mounted ready for use, in which will be seen the cylindrical case D containing the platinum spirals, which are mounted vertically in a line with one another, C_1 being at the top and C_2 at the bottom. Fig. 4 shows the instrument packed for transit by hand.

As will be seen from these illustrations, the complete instrument consists of three separate parts—the detector proper mounted on a tripod (A), the hand pump contained in a box (B), and the differential relay, with annunciators and indicating lamps contained in a box (C) (Fig. 3). Connected in series between each of the platinum wire spirals C_1 and C_2 and the coils of the relay G_1 and G_2 to which they are joined is a small low resistance annunciator coil. These two coils are marked respectively A_1 and A_2 in Fig. 1, and, as mentioned above, are contained in box C. When the main switch of the instrument con-

tained in this box is closed, the annunciators indicate visually whether the currents are actually passing through both of the platinum spirals. In the event of either of the platinum spirals being fused or broken, the corresponding annunciator reads either "dead or "alive."

The electric circuits of the relay, which are quite separate from those of the platinum spiral circuit, are, for the sake of simplicity, not shown in Fig. 1, but are shown separately in a diagrammatic form in Fig. 2. In this diagram the relay tongue marked "*t*" moves between two stops S_1 and S_2, and is itself connected to a point between two electric incandescent carbon lamps marked R and W. These two incandescent lamps are arranged in series across the supply mains to which the detector is connected. The lamp R is contained in a red glass, and the other, W, in a colourless glass shade.

It is evident that when the relay tongue is against either of the stops S_1 or S_2, the corresponding lamp is short-circuited through the stop and relay tongue, and is therefore extinguished, while the other lamp has the full voltage of the supply mains on it and is therefore burning at full brightness. In the diagram shown in Fig. 2, the red light R is shown short-circuited, and the white lamp W is lighted.

This condition is the normal condition of the detector when connected to the mains with air under test being pumped through it if the air contains no inflammable gas or vapour.

Let us suppose that the instrument is connected to the mains, then a current of electricity flows through the series of coils C_1, A_1, G_1 (Fig. 1), and approximately the same current flows through the series of coils C_2, A_2, G_2. If the relay tongue is then properly adjusted for these particular currents, it will rest, as shown in Fig. 2, so that the white lamp W is burning and the red lamp R is extinguished, whilst the annunciators A_1 and A_2 will each show "alive."

It should be remarked here that it has been found necessary that the current passing through the platinum spirals C_1 and C_2 should be sufficient to maintain them at a temperature ranging between that of a dull red heat just visible in daylight down to a temperature at which paper is just scorched in order that the chemical reaction between the oxygen and the combustible gas mixed with it shall occur readily and with certainty. By working at this initial temperature, the temperature rise produced on the platinum spiral C_1, owing to the action of the combustible gas or vapour, is much more marked, and thus, by taking advantage of the change of resistance consequent on this temperature rise, permits of the certain detection of much smaller percentages of the combustible gases or vapour in the atmosphere under examination than would be otherwise possible.

The resistance of the annunciator coils A_1 and A_2 and the relay coils G_1 and G_2 are so low that the currents passing through them do not even sensibly warm them.

As the electric circuits through the platinum spirals and the relay coils shown in Fig. 1, and those through the indicating lamps shown in

Fig. 2 are both in parallel across the supply mains, directly the current is switched on to the instrument and the pump is set in operation by turning the handle attached to it, a current of air is pumped over the hot platinum spirals. If no combustible gas or vapour is present in this air stream, the white lamp remains lighted, whilst the red lamp, being short-circuited, shows no light. If, now, the air passing through the instrument becomes contaminated with a combustible gas or vapour, the temperature of the lower platinum spiral C_2 remains unaffected, as the air does not come directly into contact with it. It does, however, come into contact with the upper platinum spiral C_1, and as the combustible mixture burns by the catalytic action of the surface of the hot platinum, it further heats the wire to a degree corresponding with the amount of inflammable gas or vapour present in the air. The result is that there is a corresponding rise in the resistance of the platinum coil C_1, and this causes a diminution of the current flowing through the relay coil G_1.

The diminution of the current in C_1 causes the release of the relay tongue, and it therefore swings over against the other stop S_2. This action breaks the short circuit of the red lamp, which becomes lighted, whilst the white lamp is at the same time short-circuited, and thus extinguished, and by this means a visual signal is given that a definite percentage of inflammable gas or vapour is present in the air under test. In parallel with the red signal lamp is connected the circuit of a valve coil V, and in some cases a single-stroke electric bell is also connected in parallel with the red lamp. The use of the bell is to supplement the visual lamp signal (the white lamp becoming extinguished and the red lamp lighted) of the presence of combustible gas by an aural one. It may be installed at any distant point such as in or near the compartment under test. The valve coil actuates a gas cut-off valve which is described below.

It is now necessary to point out two further very important devices upon which the successful action of this apparatus largely depends. These devices consist of :—

1. *A Current Vibrator.*—An arrangement for causing a constant joint fluctuation of the two parallel currents flowing through the relay coils. On the portable instrument here described this is done by means of a rotary contact breaker B in the main electric circuit actuated by the motion of the pump handle.

This contact breaker periodically short-circuits an incandescent carbon filament lamp of low resistance in the main circuit, thus causing the main pressure on the instrument momentarily to fall in value about once in every 2 seconds ; the precise periods are not of very great importance, provided the action is fairly frequent and continuous.

The effect of the current fluctuation thus caused is to make the action of the relay, which contains iron-cored electromagnets, much more sensitive, and is, in fact, a method of avoiding hysteresis effects in the magnetised iron in the relay coils. Such hysteresis effects cause the magnetisation of the iron to lag behind the magnetising force and

can, as is well known, be overcome mechanically by tapping the relay. The use of a fluctuating current is, however, generally more satisfactory than a tapping device. This device for causing the current to fluctuate periodically can also be very conveniently carried out by periodically injecting an E.M.F. into the circuit by means of a coil rotating in a magnetic field, or by a magnet moving through or over a stationary coil, or by other similar known methods of producing an injected E.M.F. By whatever means this reduction of hysteresis is effected, namely, either by a varying current produced by changes of resistance or E.M.F. in the actuating circuits, or by a mechanical or electro-magnetic tapper or vibrator, or by a small varying magnetic field superimposed on that of the relay from a varying current in a separate circuit, in every case the resultant effect is the same, the certainty and sensibility of an electric magnetic indicator, or relay containing iron, is markedly increased.

2. *The Gas Cut-off Valve.*—The duty of this valve is to cut off the stream of air containing the combustible gas or vapour directly the proportion of the combustible material present in the air under test is large enough to raise the temperature of the platinum sufficiently to cause the relay to signal the fact.

Thus, in the detectors here described, directly the temperature of the exposed platinum wire rises sufficiently to cause the relay tongue to unshort-circuit the red lamp, not only does the red lamp light up and, if desired, a bell ring, but at the same time the current passes round the coils of the valve V and actuates this, cutting off the stream of mixed air and combustible gas flowing over the exposed coil and opens it to a pure air supply. Thus the exposed coil ceases to rise in temperature due to its catalytic combustion of the combustible gases or vapour present in the stream of air under test, but it is also further cooled by a stream of pure air being drawn in over the coil by the combined chimney action of the hot tube and the ejector effect of the gases from the pump travelling along a byepass across the outer end of the tube containing the platinum coil C_1. These two actions combined cause the wire to drop rapidly to its original temperature when the relay tongue swings back once more into its original position and the red lamp is again short-circuited and extinguished, and the white lamp lights up once more. The cycle is thus completed, and as the stream of mixed air and combustible gas or vapour again flows through the instrument and over the surface of the exposed platinum coil as before, the red lamp will once again light up and the cycle will be repeated indefinitely until the instrument is switched out of circuit, or the supply of air under test once more becomes free from combustible gas or vapour.

The particular instrument here described is only one of a class, and is primarily designed for employment on board warships, or other vessels, for testing coal bunkers, double bottoms, oil tanks, etc., or any confined space which is suspected of containing combustible gas or vapour. The instrument is connected to the electric-light system either

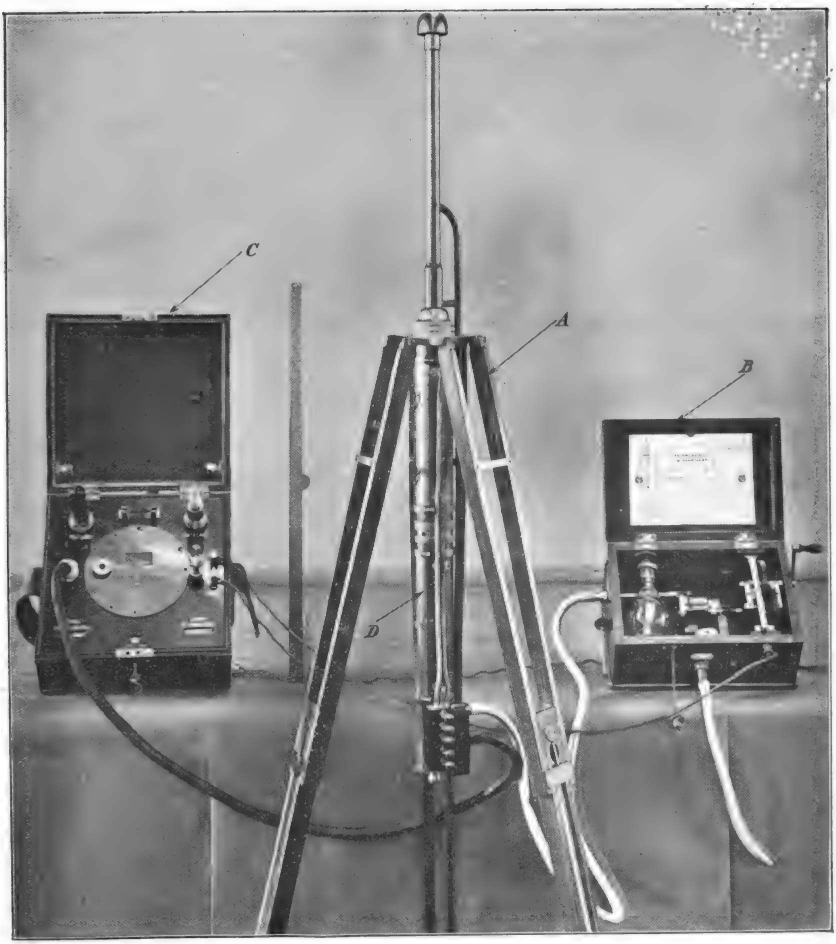

FIG. 3

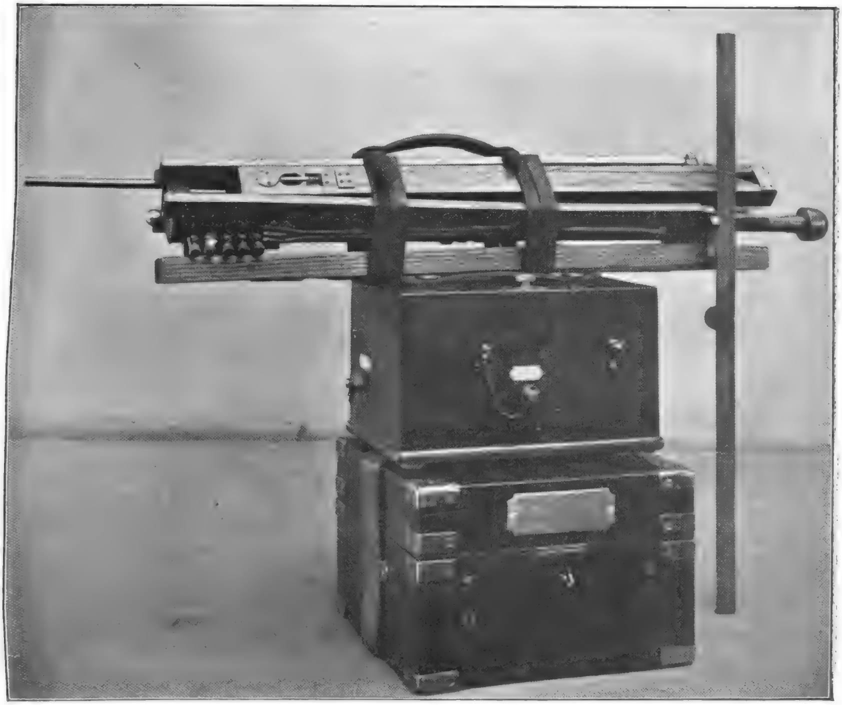

FIG. 4.

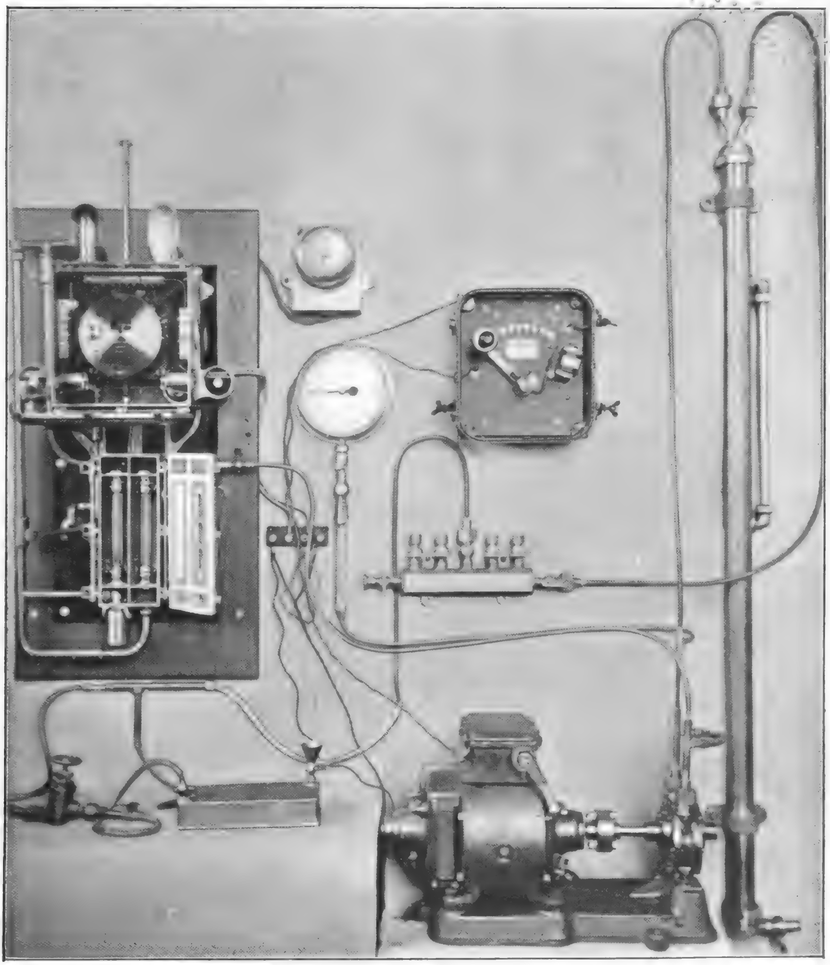

FIG. 5.

on a ship or from the shore by wandering leads, and is set up near, but not within, the space to be tested. A flexible tube is taken into the space to be examined, and the air pumped through it as above described.

The Philip and Steele inflammable vapour detector has also been made in a non-portable type, shown in Fig. 5, based on the same principle, and destined to act as a sentinel detector on the air of any space which it is considered may be dangerous from the accumulation of combustible gases or vapours. It may be left to itself, and directly the combustible material is diffused in the air of the space under its guardianship it will immediately give visible and audible indications at any desired point or points at any distance, and will continue to do so until either the combustible gas or vapour disappears, or until the appeals of the detector that the space may be ventilated, or otherwise dealt with, are attended to. Used in this manner it has been found that this sentinel detector may be employed with advantage on warships, submarines, petrol-tank vessels, coal-mines, producer gas installations, gasworks, oil-tank, land, and ship depôts, boiler plants on which it is desired to test the condition of the air, and for many other purposes.

The action of this instrument is identical with that of the portable type above described, but the hand pump is replaced by a continuously running motor-driven pump, the motor being driven straight off the supply mains, and the pump sucking air from one or more points in the compartment under test.

It has been found that if the sentinel form of detector is installed upon the bulkheads of a ship or other structure which can be relied upon to be kept in a state of sufficient vibration whilst the detector is in use by means of the transmission of the vibration of the pump motor of the detector or of the vibration caused by the vibration of the machinery of the ship itself, a special mechanical vibrating device or current fluctuating device is not necessary, but that otherwise to secure the maximum sensibility and quickness of action, some such special design as those described above must be employed.

In the sentinel form of the detector the component parts are mounted together on a vertical plate, as will be seen from Fig. 5, and are contained in two very substantial locked gas-tight cases which are absolutely foolproof. If the cases are opened for any purpose the electric current is automatically cut off from the whole of the instrument by an enclosed gas-tight switch, and the electric circuit cannot again be closed until the protective case is once more shut.

The exterior indicating annunciators on the detector show by inspection directly the current is switched on as to whether the instrument is in correct order in all respects, and as to whether the electrical and air currents are flowing and of the correct value.

The sensitiveness of the detector is unaffected by a variation of 20 per cent. up and down in the supply pressure. The consumption of power is inappreciable, amounting to only 140 watts for the detector, plus 200 watts for the motor at 100 volts.

The platinum spirals of the detector both in the portable and sentinel types, can be easily removed and replaced like cartridge-form electrical fuses, but experiments have shown that the platinum coils will last unaltered over very long periods in constant use, certainly up to a year or two. In fact, no case has been known of a coil breaking down in use in the form of instruments now described.

The closed tube is made of a different length to the open tube in order to avoid an error in replacement.

These detectors apparently give indications equally well with all combustible gases or vapours, their action depending only upon the proportion of combustible gas or vapour present. Hydrogen, coal gas, acetylene, marsh gas, petrol vapour, carbon monoxide, and the vapours of many other combustible compounds have already been tried, and no combustible gas or vapour has yet been found which did not cause the instrument to give a satisfactory indication.

For ordinary purposes, and when fitted as a sentinel indicator, this detector is made to act when the combustible gas or vapour present in the air under test rises to one-quarter of the amount which would just render the mixture inflammable. It can, however, readily be made to indicate and record much less than this amount, namely, down to about one-fortieth of the amount necessary to render the mixture of air and gas or vapour just combustible.

The sensitiveness of the instrument can be diminished at will to any desired limit by simply turning the relay key, and thus giving the relay tongue a greater bias in one direction.

The indications given by the type of detector here described, as compared with those of a safety-lamp flame cap test speak for themselves, and are conveniently shown by passing the same gaseous current over a safety lamp contained in a testing chamber, and, after observing the cap thus exhibited, passing the same gas through the detector.

A SIMPLE GRAPHICAL CONSTRUCTION FOR DETERMINING THE EFFICIENCY OF A POLYPHASE ASYNCHRONOUS MOTOR FROM THE CURRENT (CIRCLE) DIAGRAM.

By JOHN NICHOLSON, B.Sc., Whit. Sch., Associate Member.

(*Paper received 8th March*, 1912.)

Within recent years it has been shown conclusively in numerous instances that the current (circle) diagram of the polyphase induction motor may, by means of data obtained by calculation from the dimensions of the motor or by simple experimental tests on the machine, be easily constructed. The current diagram shows primarily the change of power factor under varying load conditions of the stator current, and also, by means of additional graphical constructions, gives more or less accurately the values of the efficiency and slip for various stator currents.

Of the many forms of the current diagram which have been brought to the notice of electrical engineers in this country, one of the more recent and best is due primarily to Ossanna and latterly to Bragstad, La Cour, and others. From this current diagram may be quickly obtained values of the power factor, efficiency, and slip which agree closely with the corresponding quantities determined by actual load tests. A full description of the construction, with complete proofs, and the method of using this circle diagram will be found in "Die Wechselstromtechnik," vol. v., by Arnold and La Cour.

The graphical construction for the determination of the efficiency of the induction motor, as developed by the above authors, is, however, rather elaborate and the proof is of such a mathematical nature that only those engineers who are in addition good mathematicians will be able to appreciate the solution obtained, and a large number must be content simply to hold the accuracy of the graphical construction as proved by numerous experimental tests. A simple graphical construction which gives fairly accurate results may consequently be of interest to electrical engineers.

On certain assumptions the polyphase asynchronous motor is represented by the combination of impedances shown in the following circuit (*a*), Fig. 1.

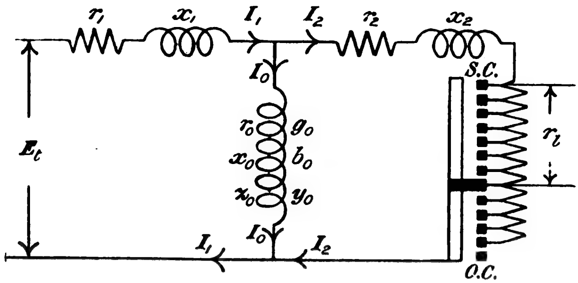

FIG. 1, Circuit (*a*).—Electric Circuit which on certain Assumptions represents the Polyphase Asynchronous Motor.

In the above circuit—

r_1 and x_1 are the stator phase resistance and reactance.
r_2 and x_2 are the rotor (equivalent) phase resistance and reactance.
$(r_1 + r_0)$ and $(x_1 + x_0)$ are the resistance and reactance corresponding to the "no-load" or "open-circuit" condition ($I_2 = 0$).
S is the slip of the rotor.
$r_2 \frac{(1 - S)}{S} = r_l$ is the non-inductive rotor phase resistance which represents the brake load on the motor.
I_1 and I_2 are the stator phase and equivalent rotor phase currents.
E_t is the stator applied terminal E.M.F.

The quantities r_1, x_1, r_2, x_2, r_0, x_0, and E_t are assumed to be constants, whilst S, $r_2 \frac{(1-S)}{S}$ or r_l vary with the brake load and produce a corresponding variation in I_1, I_2, and in the stator phase input $I_1 E_t \cos \phi_1$.

The polyphase asynchronous motor may also be represented approximately by the simpler combination of impedances shown in circuit (*b*), Fig. 2.

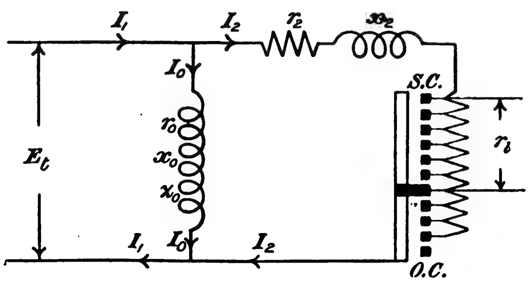

FIG. 2, Circuit (*b*).—Electric Circuit which approximately represents the Polyphase Asynchronous Motor.

In the above circuit—

r_0 and x_0 are the resistance and reactance corresponding to the "no-load" or "open-circuit" condition ($I_2 = 0$).

r_2 and x_2 are the resistance and reactance which, in parallel with r_0 and x_0, correspond to the "short-circuit" condition of the motor ($S = 1$ and $r_l = 0$).

r_2 is approximately equal to (r_1 and r_2) in circuit (a), and x_2 is approximately equal to (x_1 and x_2) in circuit (a).

S is the slip of the rotor.

$r_2 \dfrac{(1 - S)}{S} = r_l$ is the non-inductive rotor phase resistance, which represents the brake load on the rotor.

I_1 and I_2 are the stator phase and equivalent rotor phase currents.

E_t is the stator applied terminal E.M.F.

As in circuit (a), the quantities r_0, x_0, r_2, x_2, and E_t are constants, and S, r_l, I_1, I_2 and the stator phase input $E_t I_1 \cos \phi_1$ are variables.

The constants in each of the two equivalent electric circuits (a) and (b) are calculated from the "open-circuit" and "short-circuit" conditions of the induction motor. On "open-circuit" $S = 0$, r_l is infinite, and $I_2 = 0$; the "open-circuit" test therefore gives $(r_1 + r_0)$, and $(x_1 + x_0)$ in circuit (a), and r_0 and x_0 in circuit (b).

r_1 in circuit (a) is the stator phase resistance. On "short-circuit" $S = 1$, $r_l = 0$, and I_2 is a maximum. The "short-circuit" test therefore in conjunction with the previously determined constants r_1, r_0, and x_0 gives in circuit (a), r_2 and x_2 (x_1 is usually assumed equal to x_2), and in conjunction with the constants r_0 and x_0 gives in circuit (b) the remaining constants r_2 and x_2.

Examples of these calculations will be given towards the end of this article.

Current Diagram for Circuit (b), *Fig.* 2.—The current diagram for this circuit may be deduced as follows :—

Take rectangular axes Ax and Ay (Fig. 3) and set up A B to represent x_2 to some scale, B K_1 at right angles to A B to represent r_2, and K_1 P to represent $r_l = \dfrac{r_2(1 - S)}{S}$ to the same scale. Then A P represents z_2, the impedance of the branch circuit with r_2, x_2, and r_l and A K_1 represents the impedance of that branch circuit on short circuit when $S = 1$ and $r_l = 0$. The straight line K_1 P is the locus of the end of the z_2 vector.

For any electric circuit the product of the admittance y_2 and the impedance z_2 is constant and equal to unity. Let A P_2 represent to some scale the value of the admittance y_2 corresponding to the impedance z_2 represented by A P; the product A P_2 × A P will be constant. The locus of P_2 can therefore be obtained. Draw $B_2 P_2$ perpendicular to A P_2. The triangles A $B_2 P_2$ and A P B are similar, therefore A P_2/A B_2 = A B/A P, and A B_2 × A B = A P_2 × A P = constant, and hence A B_2 = constant. The locus of P_2 will therefore be

the circle on $A B_2$ as diameter. Bisect $A B_2$ at C_2, and with centre C_2 and radius $C_2 P_2$ describe this circle, cutting $A K_1$ at K. Then $A K \times A K_1 = A B_2 \times A B =$ constant, and $A K$ represents the admittance of the branch circuit on short circuit when $S = 1$ and $r_t = 0$.

For any electric circuit the E.M.F. × admittance = current, and if the E.M.F. is constant, the current will be proportional to the admittance. In the branch circuit under consideration the E.M.F. E_t is constant, and therefore the current I_2 is proportional to the admittance y_2. The vector $A P_2$ will therefore represent either the admittance y_2 to one scale or the current I_2 to some other scale. These scales are easily obtained since on the admittance scale $A B_2$ represents $\frac{1}{x_2}$ ohm, and on the current scale $A B_2$ represents E_t/x_2 amperes. $A B_2$ is there-

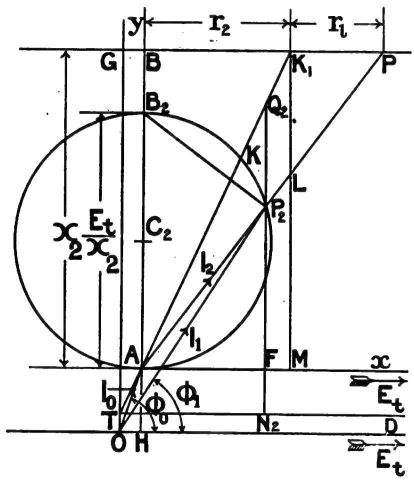

FIG. 3.—Illustrating the Construction of the Current (Circle) Diagram for Circuit (*b*), Fig. 2, and the Proof of the Expression for the Efficiency of that Circuit.

fore a wattless current, and will be at right angles to the terminal E.M.F., E_t, vector. $\cos \phi_2$ is the power factor of the branch circuit. Now set back $A O$ to represent I_0 on the current scale and draw $O D$ and $O G$ parallel to the x and y axis respectively. $\cos \phi_0$ is the power factor of the branch circuit containing r_0 and x_0, and therefore $\cos \phi_0$ and I_0 are constant. The vector $O P_2$ will represent on the current scale the stator phase current I_1, and $\cos \phi_1$ will be the corresponding power factor of the induction motor. The locus of the current vector I_1 is therefore the circle $A P_2 B_2$ on $A B_2$ as diameter. This circle is the current (circle) diagram for the electric circuit (*b*) in Fig. 2.

Produce $K A$ to meet $O G$ at T and draw $T N_2$ parallel to $O D$. Draw $Q_2 P_2 N_2$ and $K_1 L M$ parallel to $O G$.

Graphical Determination of the Efficiency.—In this circuit the watts $I_0^2 r_0$ and $I_2^2 r_2$ represent power lost in heating, and the watts $I_2^2 r_l$ represents the useful power per phase. The efficiency of the circuit is therefore—

$$\eta_2 = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{I_2^2 r_l}{I_2^2 r_l + I_2^2 r_2 + I_0^2 r_0}$$

$$= \frac{r_l/(r_l + r_2)}{1 + \dfrac{I_0^2 r_0}{I_2^2 (r_l + r_2)}} = \frac{r/(r_l + r_2)}{1 + \dfrac{E_t I_0 \cos\phi_0}{E_t I_2 \cos\phi_2}}$$

$$= \frac{r_l/(r_l + r_2)}{1 + \dfrac{I_0 \cos\phi_0}{I_2 \cos\phi_2}} = \frac{K_1 P/B P}{1 + \dfrac{O H}{A F}}$$

$$= \frac{K_1 P/B P}{T N_2/A F} = \frac{K_1 L/B A}{T N_2/A F}$$

$$= \frac{K_1 L/K_1 M}{T N_2/A F} = \frac{Q_2 P_2/Q_2 F}{Q_2 N_2/Q_2 F}$$

$$= \frac{Q_2 P_2}{Q_2 N_2}$$

The efficiency of circuit (*b*), Fig. 2, when the current I_1 is represented by $O P_2$ is equal to the ratio $Q_2 P_2/Q_2 N_2$, where $Q_2 N_2$ is the intercept of the ordinate through P_2 between the straight lines K A T and $T N_2$.

These two straight lines K A T and $T N_2$ are determined without any difficulty, since K, A, and the centre C_2 vertically above A are the three points which fix the current circle.

Current Diagram for Circuit (*a*), *Fig.* 1.—The current diagram for this circuit may be deduced in a similar manner, and is shown in Fig. 4. It is found that the current diagram is again a circle passing through the "no-load" and short-circuit" points A and K, but having its centre C_1 on a line inclined at an angle $(90 - \alpha)$ to the terminal E.M.F., E_t, where—

$$\tan\alpha = \frac{g_0 + r_1 (y_0^2 + b_0/x_2)}{b_0 + x_1 (y_0^2 + b_0/x_2) + \dfrac{1}{2 x_2}},$$

and g_0, b_0, and y_0 are the conductance, susceptance, and admittance respectively of the shunt circuit of resistance r_0 and reactance x_0.

This is approximately the current diagram for the induction motor as developed by Ossanna, Bragstad, La Cour, and others, and it has been shown in many cases that the current diagram so obtained agrees very closely with the current curve (I_1, ϕ_1) plotted from data obtained in actual load tests of motors. In practice the angle α in the current diagram is obtained from the formula—

$$\tan\alpha = \frac{I_{0w} \sin\phi_k + I_{0w_1} \cos\phi_k}{I_k + I_{0w_1} \sin\phi_k - I_{0w} \cos\phi_k},\text{*}$$

* E. Arnold and J. L. la Cour, "Die Wechselstromtechnik," vol. v. (1), p. 103, Springer, Berlin, 1909.

where I_{0w} and I_{0w_1} are the watt and the wattless components of the "no-load" current I_0.

The efficiency of circuit (*a*) is—

$$\eta_1 = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{I_2^2 r_l}{I_2^2 r_l + I_2^2 r_2 + I_0^2 r_0 + I_1^2 r_1}.$$

This expression may also for any particular value of the input current I_1 be obtained as the ratio of two lines in a manner somewhat similar to that shown above for circuit (*b*), Fig. 2. The graphical construction for the efficiency in this case is, however, not so simple, and the proof is so elaborate that it will not be given, but another, although possibly less accurate, method will be described.

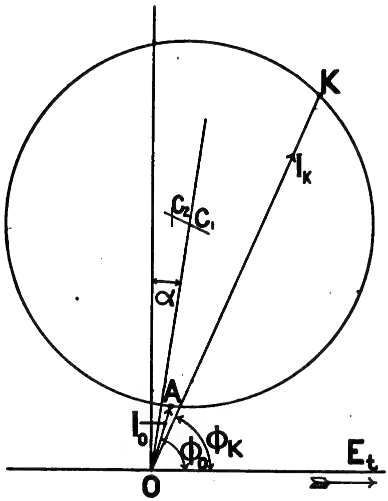

FIG. 4.—Current (Circle) Diagram for Circuit (*a*).

Comparison of Efficiencies of Circuits (*a*) *and* (*b*).—In practice it will be found that for equal currents I_1 in circuits (*a*) and (*b*) the efficiencies η_1 and η_2 of these circuits, as calculated by the formulæ given, agree very closely. Examples of this agreement are given later on.

In order therefore to determine the efficiency of circuit (*a*) for a certain current I_1 the circle diagrams for circuits (*a*) and (*b*) are drawn together in Fig. 5.

OP_1 and OP_2 represent the equal currents I_1 in the two circuits; Q_2P_2/Q_2N_2 is the corresponding efficiency of circuit (*b*), and if the above statement is correct it will also be very approximately the efficiency of circuit (*a*) corresponding to the current OP_1 or I_1.

The data for the efficiency of the circuit (*a*), and consequently for the predetermination of the efficiency of the induction motor, will not be got from the current diagram for the induction motor—or circuit (*a*)—but from the current diagram for the approximately equivalent circuit (*b*).

In practice it will be found that these circles, which are shown diagrammatically in Fig. 5, are approximately coincident. Hence $Q_1 P_1/Q_1 N_1$ will only be slightly greater than $Q_2 P_2/Q_2 N_2$ for the same value of I_1 ($O P_1 = O P_2$), and for that reason the ratio $Q_1 P_1/Q_1 N_1$ may be, and indeed is, frequently assumed to be equal to the efficiency of

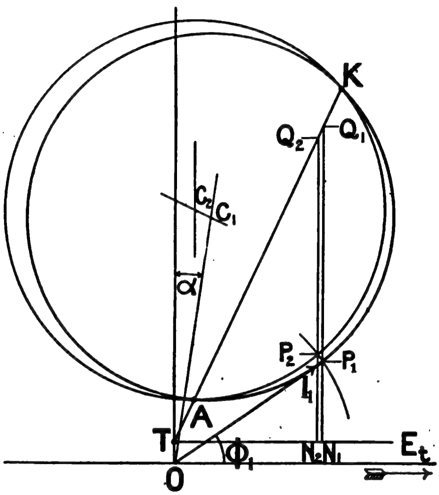

FIG. 5.—Combined Current Diagrams for Circuits (*a*) and (*b*). The distance $C_1 C_2$ is shown exaggerated.

the induction motor, and in most cases gives a close approximation to the efficiency.

In order to verify the assumption that circuits (*a*) and (*b*) have approximately equal efficiencies for equal values of the current I_1, and that the efficiency of the polyphase induction motor is given approximately by the ratio $Q_2 P_2/Q_2 N_2$ or by the ratio $Q_1 P_1/Q_1 N_1$, various tests were carried out in the James Watt Engineering Laboratories, Glasgow University, on a 6-pole 1,000 revs. per minute, 3-phase induction motor, with wound rotor of the type N.D., made by the Electrical Company, Ltd., London. This motor gives an output of 10 B.H.P., with the normal stator phase voltage of 110 volts, and phase current I_1 of 29 amperes.

Tests were carried out at 110 volts and at 149 volts stator phase voltage.

Results of Experiments on Induction Motor.

1. *Stator Phase Voltage* = 110 *Volts.*

(*a*) "No-load" test: $I_0 = 8{\cdot}68$ ampères, $W_0 \doteq 610$ watts, and $\cos\phi_0 = 0{\cdot}213$.

(*b*) "Short-circuit" test: $I_k = 111{\cdot}7$ amperes, $r_k = 0{\cdot}390$ ohm, $x_k = 0{\cdot}904$ ohm, and $\cos\phi_k = 0{\cdot}396$.

(*c*) Stator phase resistance, $r_1 = 0{\cdot}160$ ohm.

(*d*) Load test with eddy current brake.

Stator Phase Current. I_1 (amperes).	Power Factor. $\cos\phi_1$.	Efficiency $= \frac{\text{Brake Load}}{\text{Input Watts}}$	Remarks.
8·68	0·213	0·000	Load test with stator.
10·00	0·485	0·620	Phase voltage = 110 volts.
12·50	0·697	0·760	The watts input to the motor was measured by the "2-wattmeter" method, and the power factor, $\cos\phi_1$, was got from the ratio of the two wattmeter readings.
15·00	0·780	0·805	
20·00	0·845	0·830	
25·00	0·869	0·832	
30·00	0·877	0·826	
35·00	0·379	0·816	

Determination of the Constants in Circuits (*a*) *and* (*b*).

I. *Circuit* (*a*), *Fig.* 1: $r_1 = 0{\cdot}160$ ohm. Since we have not sufficient data to fix x_1 or x_2 we assume $x_1 \doteq \frac{1}{2}\,x_k \doteq 0{\cdot}450$ ohm. Then from the "no-load" test (knowing x_1 and r_1) we get $r_0 = 2{\cdot}54$ ohm and $x_0 = 11{\cdot}93$ ohm, and finally from the "short-circuit" tests and the above values for r_1, x_1, r_0, and x_0 we get $r_2 = 0{\cdot}245$ ohm and $x_2 = 0{\cdot}471$ ohm. Tan $a = 0{\cdot}0371$.

II. *Circuit* (*b*), *Fig.* 2: From the "no-load" tests we get $r_0 = 2{\cdot}70$ ohms and $x_0 = 12{\cdot}38$ ohms, and from the "short-circuit" test ($r_l = 0$) we get $r_2 = 0{\cdot}438$ ohm and $x_2 = 0{\cdot}972$ ohm.

The current diagrams for circuits (*a*) and (*b*) are shown in Fig. 6. The normal working range of these diagrams extends from A to P_1 or from A to P_2. OP_1 or OP_2 represents the full-load stator phase current $I_1 = 30$ amperes, and the points P_1 and P_2 are so close together that the ordinates $Q_1 P_1 N_1$ and $Q_2 P_2 N_2$ practically coincide.

Calculation of the Efficiencies and Power Factors of Circuits (*a*) *and* (*b*) *for varying Values of the Current* I_1.—Different values for the load resistance r_l in circuits (*a*) and (*b*) were assumed, and corresponding

values of the currents I_1 and I_2, the efficiency and the power factor, were calculated for each circuit.

The following results were obtained :—

Circuit (a).—E_t = 110 Volts per Phase.

r_l Ohms.	I_1. Amperes.	I_2. Amperes.	Efficiency, η_1.	Power Factor, Cos ϕ_1.	Remarks.
∞	8·68	0	0	0·213	
30	10·0	3·48	0·636	0·520	These results were calculated from the constants in circuit (*a*).
20	11·0$_3$	5·19	0·715	0·620	
15	12·2$_0$	6·86	0·761	0·692	
12	13·47	8·52	0·789	0·745	
9	15·7$_3$	11·2$_2$	0·817	0·801	
7	18·4$_0$	14·2$_1$	0·832	0·839	
6	20·4$_2$	16·3$_9$	0·838	0·857	
5	23·2$_3$	19·3$_5$	0·841	0·872	
3	27·3$_5$	23·6$_0$	0·839	0·883	
2	33·8$_0$	30·1$_3$	0·826	0·886	
0	111·7	103·2	0	0·396	

Circuit (b).—E_t = 110 Volts per Phase.

r_l. Ohms.	I_1. Amperes.	I_2. Amperes.	Efficiency, η_2.	Power Factor, Cos ϕ_1.	Remarks.
∞	8·86	0	0	0·213	
30	10·2$_0$	3·61	0·652	0·536	These results were calculated from the constants in circuit (*b*).
20	11·3$_3$	5·38	0·728	0·637	
15	12·6$_4$	7·11	0·771	0·708	
12	14·0$_5$	8·82	0·797	0·757	
10	15·5$_1$	10·5$_0$	0·814	0·793	
7	19·4$_0$	14·6$_6$	0·835	0·845	
6	21·5$_6$	16·9$_0$	0·839	0·861	
5	24·6$_1$	19·9$_1$	0·840	0·872	
4	28·9$_3$	24·2$_1$	0·836	0·881	
3	35·7$_1$	30·8$_0$	0·821	0·881	
0	111·7	103·2	0	0·396	

Curves showing these efficiencies and power factors plotted as ordinates on a current (I_1) base are shown in Fig. 8. The full lines represent the calculated values, and the small circles represent the actual experimental results.

An analysis of the above results will show that at low loads the efficiency of circuit (*a*) exceeds that of circuit (*b*) by 0·2 of 1 per cent. whilst at full load the calculated efficiencies for (*a*) and (*b*) agree

exactly, and are approximately 0·7 of 1 per cent. greater than the actual efficiency of the motor as determined by experiment.

The power factor of circuit (*a*) is consistently 0·5 of 1 per cent. higher than that of circuit (*b*) and 0·9 of 1 per cent. higher than the power factor of the motor as determined by experiment. This means that the true current diagram for the motor (or the diagram obtained by

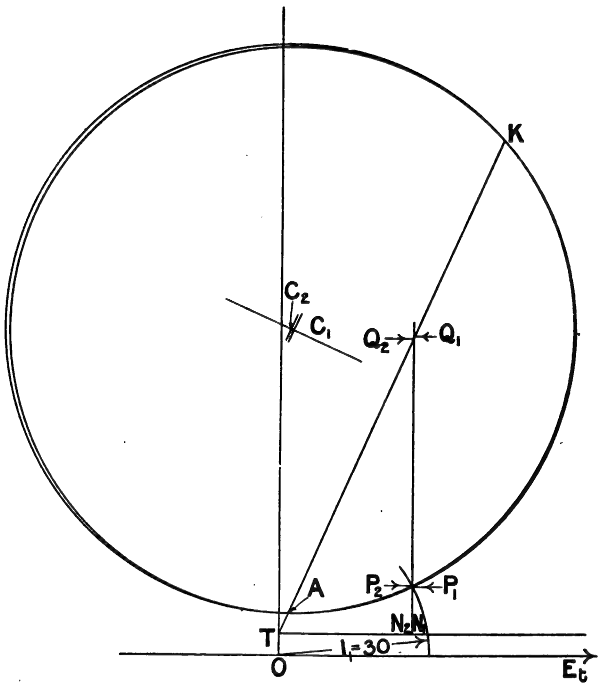

FIG. 6.—Stator Phase Voltage, 110 Volts. Current Diagrams for Circuits (*a*) and (*b*).

plotting corresponding, experimentally determined, values of I_1 and ϕ_1) lies inside both of the current circles (*a*) and (*b*). If, then, these two current circles were made to coincide with the true current diagram, the ratio Q_2P_2/Q_2N_2 would be diminished, and the efficiencies of circuits (*a*) and (*b*) would also be diminished, and would approach more closely to the actual (experimentally determined) efficiency of the motor.

With regard to the probable accuracy of the experimental results obtained by the load test, the watts input to the motor was obtained by the two-wattmeter method, and the power factors were deduced from

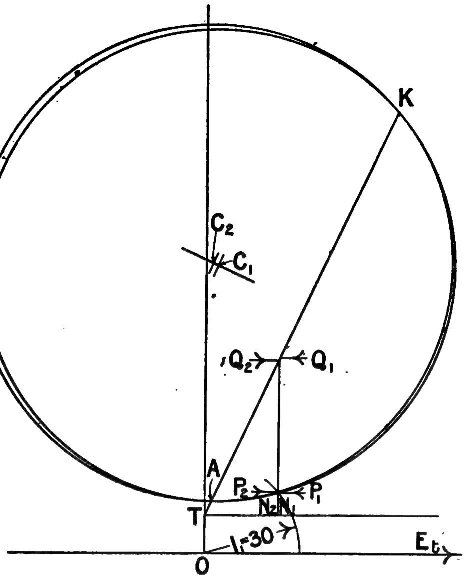

FIG. 7.—Stator Phase Voltage = 149 volts. Current Diagrams for Circuits (*a*) and (*b*).

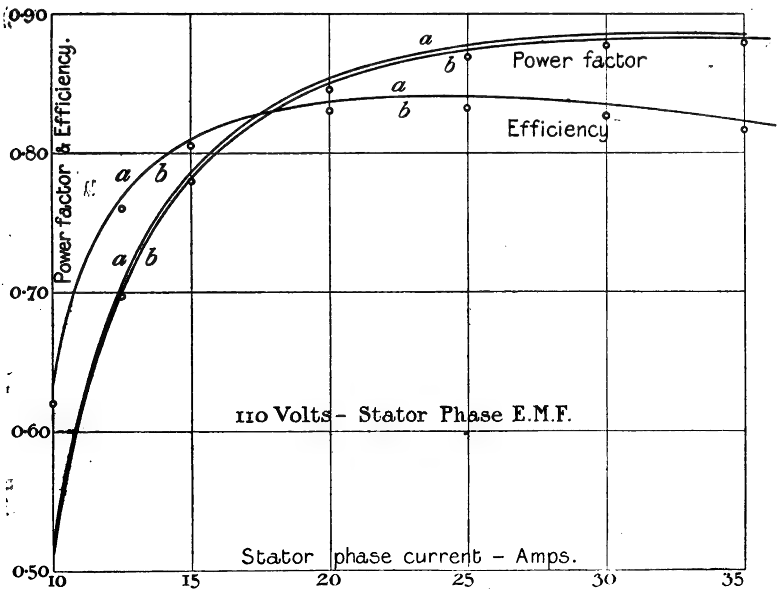

FIG. 8.—E_t = 110 Volts. Efficiencies and Power Factors plotted in a Current (I_1) Base The Full Lines give the calculated Values for Circuits (*a*) and (*b*), and the Circles give the experimentally determined Values.

the ratio of the wattmeter readings. The power factors so obtained agreed within 0·4 of 1 per cent. with the corresponding values obtained directly from the watts and volt-ampere input. Cos ϕ_1 is therefore probably correct to 0·2 of 1 per cent. The efficiency at full load is probably correct to within ½ of 1 per cent. The eddy current brake has its "weighing system" mounted on ball bearings. The balance was checked before and after the experiment, and a separate direct determination of the "no-load" losses in the brake was made. These "no-load" brake losses, which amounted to almost 3½ per cent. of the normal full load output of the motor, were then added to the recorded brake load, giving the total brake load of the induction motor.

2.—*Similar Experiments were made on the Induction Motor with the Stator Phase E.M.F.* = 149 *Volts.*

(*a*) "No-load" test.—$I_0 = 16·64$ amperes; $W_0 = 938$ watts; $\cos\phi_0 = 0·126$.
(*b*) "Short-circuit" test.—$I_k = 151·4$ amperes; $r_k = 0·390$ ohm; $x_k = 0·904$ ohm, and $\cos\phi_k = 0·396$.
(*c*) Stator phase resistance $r_1 = 0·160$ ohm.
(*d*) Load test with eddy current brake.

Stator Phase Current. I_1.	Power Factor, $\cos\phi_1$.	Efficiency $= \frac{\text{Brake Load}}{\text{Input Watts}}$.	Remarks.
16·64	0·128	0·000	Load test at $E_t = 149$ volts. Phase Voltage.
17·5	0·359	0·656	
20·0	0·570	0·790	
22·0	0·655	0·821	
25·0	0·730	0·844	
28·0	0·775	0·851	
30·0	0·797	0·854	
32·0	0·815	0·855	
35·0	0·834	0·855	

Determinaion of the Constants in Circuits (*a*) *and* (*b*).

Circuit (*a*), *Fig.* 1:—$r_1 = 0·160$ ohm. In the preceding example we assumed $x_1 = 0·450$ ohm and then found $x_2 = 0·471$ ohm, but since in this machine x_1 is probably greater than x_2, it will be more accurate to assume $x_1 = 0·500$ ohm. Then from the "no-load" test we get $r_0 = 0·969$ ohm and $x_0 = 8·385$ ohm, and finally from the "short-circuit" test and the above values

for r_1, x_1, r_0, and x_0 we get $r_2 = 0{\cdot}251$ ohm and $x_2 = 0{\cdot}419$ ohm. Tan $a = 0{\cdot}0407$.

II. *Circuit* (*b*), *Fig.* 2.—From the "no-load" test we get $r_0 = 1{\cdot}130$ ohm and $x_0 = 8{\cdot}885$ ohms, and from the "short-circuit" test we then get $r_2 = 0{\cdot}470$ ohm and $x_2 = 0{\cdot}995$ ohm.

Calculations of the Efficiencies and Power Factors of the Circuits (*a*) and (*b*) for varying Values of the Current I_1.

I.—*Circuit* (*a*).—$E_t = 149$ *Volts per Phase.*

r_l. Ohms.	I_1. Amperes.	I_2. Amperes.	Efficiency, η_1.	Power Factor, Cos ϕ_1.	Remarks.
∞	$16{\cdot}6_4$	0	0	0·128	
50	$17{\cdot}1_7$	2·79	0·552	0·275	These results were calculated from the constants in circuit (*a*).
30	$17{\cdot}7_5$	4·62	0·666	0·363	
20	$18{\cdot}7_3$	6·88	0·740	0·458	
15	$19{\cdot}9_3$	9·11	0·782	0·536	
12	$21{\cdot}2_7$	$11{\cdot}3_1$	0·808	0·599	
10	$22{\cdot}7_5$	$13{\cdot}4_6$	0·824	0·649	
8	$25{\cdot}1_3$	$16{\cdot}6_4$	0·838	0·706	
7	$26{\cdot}9_0$	$18{\cdot}8_6$	0·844	0·735	
6	$29{\cdot}3_3$	$21{\cdot}7_5$	0·848	0·765	
5	$32{\cdot}7_7$	$25{\cdot}6_8$	0·849	0·795	
4	$37{\cdot}9_7$	$31{\cdot}3_2$	0·845	0·820	
0	151·4	143·9	0	0·396	

II.—*Circuit* (*b*).—$E_t = 149$ *Volts per Phase.*

r_l. Ohms.	I_1. Amperes.	I_2. Amperes.	Efficiency, η_2.	Power Factor, Cos ϕ_1:	Remarks.
∞	$16{\cdot}6_4$	0	0	0·128	
50	$17{\cdot}3_3$	2·95	0·579	0·291	These results were calculated from the constants in circuit (*b*).
20	$19{\cdot}2_9$	7·27	0·758	0·485	
15	$20{\cdot}7_4$	9·6	0·796	0·564	
12	$22{\cdot}3_8$	11·9	0·818	0·625	
10	$24{\cdot}1_2$	$14{\cdot}1_8$	0·831	0·672	
8	$26{\cdot}8_8$	$17{\cdot}4_8$	0·843	0·724	
7	$28{\cdot}9_3$	$19{\cdot}7_8$	0·846	0·750	
6	$31{\cdot}6_9$	$22{\cdot}7_7$	0·848	0·776	
5	$35{\cdot}5_6$	$26{\cdot}8_1$	0·847	0·801	
4	$41{\cdot}2_8$	$32{\cdot}5_5$	0·839	0·821	
0	151·4	143·9	0	0·396	

Curves showing these efficiencies and power factors plotted as ordinates on a current (I_1) base are shown in Fig. 9. The full lines represent the calculated values, and the small circles represent the actual experimental results.

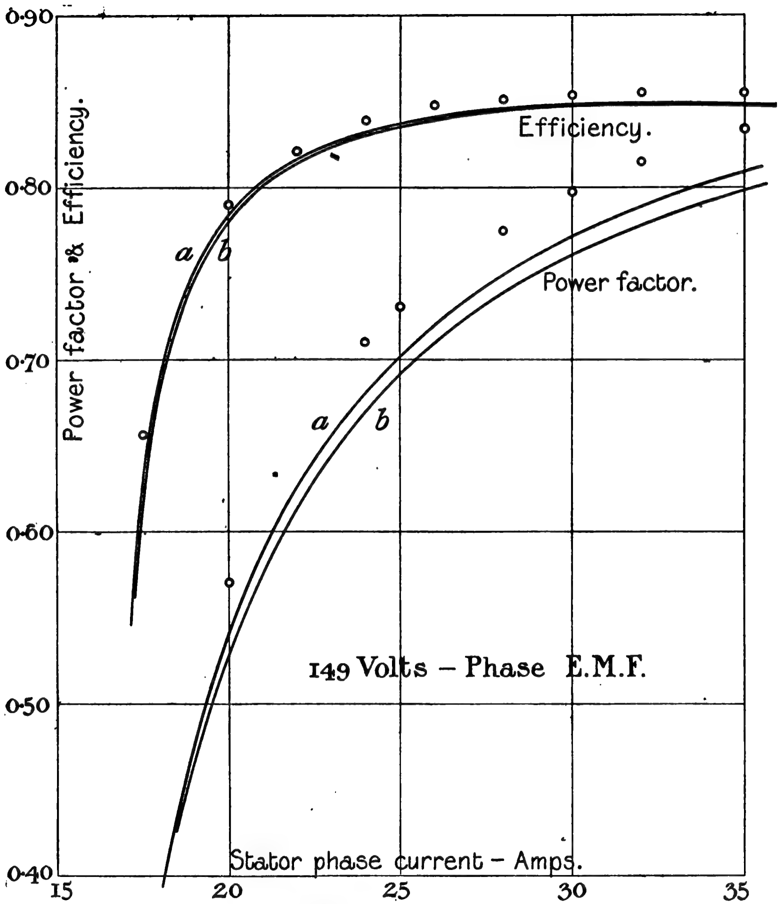

FIG. 9.—Et = 149 Volts. Efficiencies and Power Factors plotted on a Current (I_1) Base. The Full Lines give the calculated Values for Circuits (a) and (b), and the Circles give the experimentally determined Values.

An analysis of these results shows that at full-load current the efficiency of circuit (a) exceeds that of circuit (b) by only 0·2 of 1 per cent., whilst it is less than the actual efficiency of the motor by 0·5 of 1 per cent.

At full-load current I_1 the power factor of circuit (*a*) is almost 1 per cent. higher than that of circuit (*b*), but is about $2\frac{1}{2}$ per cent. less than the actual power factor of the motor as calculated from the ratio of the wattmeter readings, or from the ratio of the corresponding watt and volt-ampere inputs on the load test. The true current diagram for the motor therefore now lies outside the circles for circuits (*a*) and (*b*) instead of inside, as in the former case at normal voltage. The ratio $Q_2 P_2/Q_2 N_2$ would therefore be increased, and the efficiency of circuits (*b*) and (*a*) would be increased if the circle diagrams for these circuits were to coincide with the true current diagram for the motor.

Position of the Centre of the Circle which is the true Current Diagram for the Induction Motor.—A series of load tests on the above 10-B.H.P. 110-volt 3-phase induction motor at stator phase voltages, ranging from 50 volts to 170 volts, showed that the centre of the circle gradually drifted to the right as the voltage increased. When the stator phase voltage was 50 volts the centre was vertically above the origin o, and the true current diagram lay well inside the corresponding current diagrams for the equivalent circuits (*a*) and (*b*). At the normal voltage of 110 volts the centre of the true current diagram was practically vertically above the corresponding "no-load" point A, and at 170 volts the centre lay still further to the right, and the true current diagram was well outside of the corresponding current circles for circuits (*a*) and (*b*).

In practice the angle α, giving the position of the centre C_1 for the approximately equivalent circuit (*a*), is obtained from the following equation :—

$$\tan \alpha = \frac{I_{ow} \sin \phi_k + I_{ow_1} \cos \phi_k}{I_k + I_{ow_1} \sin \phi_k - I_{ow} \cos \phi_k}.$$

This angle α differs slightly from that as calculated from the constants of circuit (*a*).

The calculated efficiencies of the two circuits (*a*) and (*b*) have been shown to agree very closely over the whole working range of the current I_1 for the normal stator phase voltage, 110 volts, and for a stator phase voltage of 149 volts. The calculated efficiencies also agree very approximately with the actual experimental results. The ratio $Q_2 P_2/Q_2 N_2$ will probably, therefore, in most cases give results which are correct to about $\frac{1}{2}$ per cent.

In order to demonstrate the accuracy with which the ratios Q P/Q N may be measured graphically in practice the following table gives values of these ratios obtained from Figs. 6 and 7 before these figures were inked in (see page 312).

These tables show that if proper precautions are taken the efficiency obtained graphically from the circle diagram for circuit (*a*) for all loads greater than $\frac{1}{3}$ full load agrees within 0·2 of 1 per cent. with the corresponding calculated efficiency. The chief precaution is to find the point T where the line K A crosses the axis of wattless

current. This point, or the intercept O T, may be obtained with great accuracy since the co-ordinates of the points K and A are given by the "no-load" and the "short-circuit" tests. If the intercept O T is not

I. *Stator Phase Voltage,* 110 *Volts.*

I_1. Amperes.	$\frac{Q_1 P_1}{Q_1 N_1}$. (From Fig. 6.)	Efficiency of Circuit (*b*), Fig. 2. Graphical Determination. $\frac{Q_2 P_2}{Q_2 N_2}$. (From Fig. 6.)	Efficiency of Circuit (*b*), Fig. 2. Calculated from the Constants of the Circuit and plotted in Fig 8.	Remarks.
10·0	0·632	0·631	0·635	Columns (3) and (4) should give equal values.
12·5	0·771	0·764	0·767	
15·0	0·810	0·805	0·808	
20·0	0·840	0·835	0·836	
25·0	0·843	0·838	0·839	
30·0	0·837	0·833	0·835	
35·0	0·827	0·823	0·823	

II.—*Stator Phase Voltage,* 149 *Volts.*

I_1. Amperes.	$\frac{Q_1 P_1}{Q_1 N_1}$. (From Fig. 7.)	Efficiency of Circuit (*b*), F.g. 2. Graphical Determination. $\frac{Q_2 P_2}{Q_2 N_2}$. (From Fig. 7.)	Efficiency of Circuit (*b*), F.g. 2. Calculated from the Constants of the Circuit and plotted in Fig. 9.	Remarks.
17·5	0·594	0·593	0·618	Columns (3) and (4) should give equal values.
20·0	0·792	0·780	0·770	
22·0	0·822	0·812	0·814	
25·0	0·844	0·834	0·835	
28·0	0·853	0·843	0·844	
30·0	0·856	0·848	0·847	
32·0	0·858	0·848	0·849	
35·0	0·854	0·847	0·847	

calculated, then the position of the point T may easily be varied within limits which would give widely different values for the ratio Q P/Q N, and hence for the efficiency of the motor. For the 110-volt test the

distance O T is 4·4 amperes, and for the 149-volt test the distance O T is 12·1 amperes.

In conclusion, the author desires to express his thanks to the Carnegie Trust for the Universities of Scotland for the loan of ammeters and wattmeter for the carrying out of the actual tests on the induction motor, and to Mr. C. W. Marshall, B.Sc., and Mr. D. Weir for assistance with the various calculations.

THE TUNGSTEN FILAMENT LAMP ON ALTERNATING CURRENT.

By LANCELOT W. WILD, Member.

(*Paper received 25th April, 1912.*)

An incandescent lamp running on an alternating-current circuit does not emit a constant flux of light, but the light fluctuates, following on a reduced scale the instantaneous variations of the current.

As the instantaneous candle-power is independent of the direction of the instantaneous current it follows that the frequency of the light fluctuations must be double the frequency of the current.

The fluctuation of candle-power is due to the filament cooling to a certain extent between the peaks of the current wave. It follows, therefore, that the amplitude of these fluctuations must depend upon the frequency of the circuit and the thermal capacity of the filament.

The fluctuation in the light emission from incandescent lamps can be conveniently examined by means of an instrument which may be called a strobo-photometer.

The Strobo-photometer.—The essential parts of the strobo-photometer are shown in elevation in Fig. 1 :—

L is the lamp under examination. This is maintained in a fixed position.

B is a Bunsen disc of rather unusual form. The boundary between the opaque and translucent portions is a vertical line. The disc is viewed at 45 degrees but on one side only. This is also stationary.

C is the comparison lamp. This is mounted on a wheeled carriage and is furnished with a pointer which indicates on a scale in the usual manner the distance or square of the distance of this lamp from the Bunsen disc.

Between the Bunsen disc and the lamp under examination, and only about ½ in. from the former, runs a cardboard disc D driven by a synchronous motor M. In this disc are two sector-shaped gaps diametrically opposite to each other, each covering an arc of 5 degrees.

The Bunsen disc is thus exposed to the rays from the lamp under examination twice in each revolution of the motor armature, and for a comparatively brief period only each time.

As the revolving disc cuts off about 97 per cent. of the light, it is necessary that the lamp and Bunsen disc be rather close together if adequate illumination is to be obtained. This necessitates having the distance between the lamp under examination and Bunsen disc rigidly fixed. The photometer is balanced by altering the position of the comparison lamp.

The motor is a simple 2-pole machine with laminated H-armature furnished with a two-part commutator and series-wound laminated fields. Such a machine will start up on alternating current as on continuous current, but shows a marked preference to running in synchronism as soon as it gets up to synchronous speed.

When the motor is running non-synchronously, the cardboard disc merely acts like an ordinary Talbot disc, and the average instantaneous value of the candle-power is measured when the comparison lamp is brought up to the position of balance.

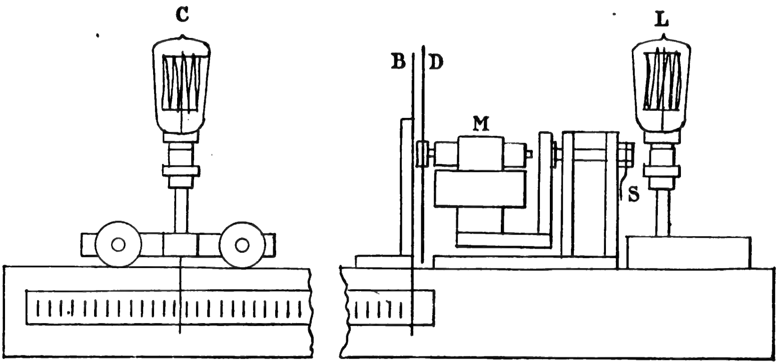

FIG. 1.

When the motor is running synchronously, the lamp is always exposed in the same phase, and the measurement obtained represents an instantaneous value of the candle-power.

The phase angle is varied by swinging the motor round on its axis. A pointer and scale S indicate the phase angle.

The instantaneous value of candle-power can thus be measured at regular phase intervals throughout a half period of current and a whole period of light fluctuation and then the curve can be plotted out.

Thermal Capacity and Amplitude of Light Fluctuation.—A number of lamps of varying voltages and candle-powers were selected and calibrated at 1·3 watts per candle-power. The currents taken by the lamps were then measured and also the maximum, minimum, and mean instantaneous values of their candle-powers, at 25 periods.

The results of these tests are shown by the curves in Fig. 2. The ordinates represent relative candle-power and the abscissæ amperes

at 1·3 watts per candle-power. The range is from 0·1 to 0·65 ampere, the maximum instantaneous candle-power being 1·58 times the mean for the finest filament and 1·11 times the mean for the stoutest filament. The minimum ranges from 0·44 to 0·90.

The 0·1 ampere lamp was also tested at 50 periods and a maximum value of 1·30 and a minimum of 0·71 were found, which is practically half the fluctuation at 25 periods.

The whole curve of fluctuation was plotted out in the case of this 0·1 ampere lamp at 25 periods and is given in Fig. 3.

It is to be noted that the height of the peak is greater than the depth of the valley, to make up for which the width of the valley is the greater.

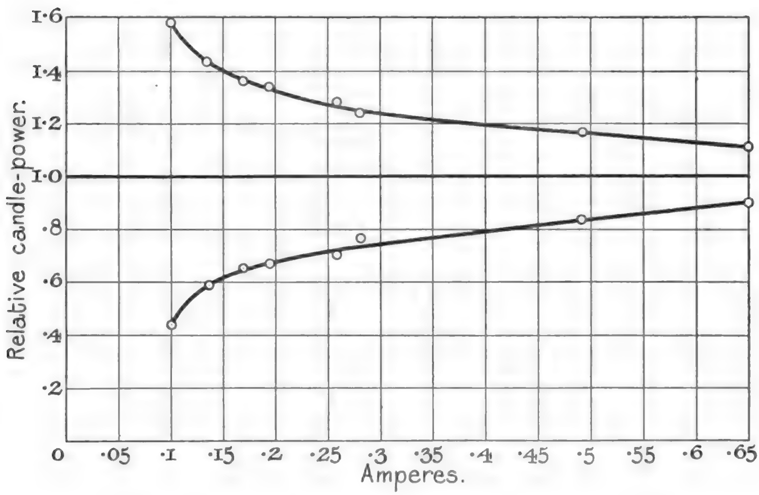

FIG. 2.

With such a wide fluctuation it is hardly to be expected that the mean value of the candle-power should be altogether independent of frequency.

Candle-power and Frequency.—The lamp taking 0·1 ampere at 1·3 watts per candle-power, already referred to, was tested for mean horizontal candle-power and consumption on continuous current and then on alternating at 50 and 25 periods. At 50 periods an increase of 0·7 per cent. in candle-power was observed over that found on continuous current. At 25 periods the excess was as much as 2·5 per cent.

No change was observed in the watts, which means that any change there may have been was less than 1 part in 1,000.

It is rather interesting that the efficiency of a lamp should thus

prove to be slightly different on alternating current from what it is on continuous current.

Another lamp taking about 0·2 ampere at 1·3 watts per candle-power was also tested. At 25 periods an excess of 0·75 per cent. in candle-power over the value on continuous current was observed.

This second test is reasonably consistent with the first, as the range of fluctuation of a 0·2 ampere lamp at 25 periods is about the same as a 0·1 ampere lamp at 50 periods.

Effect of Fluctuating Temperature on Current Wave.—A fluctuating temperature must cause a fluctuation of the resistance of the filament.

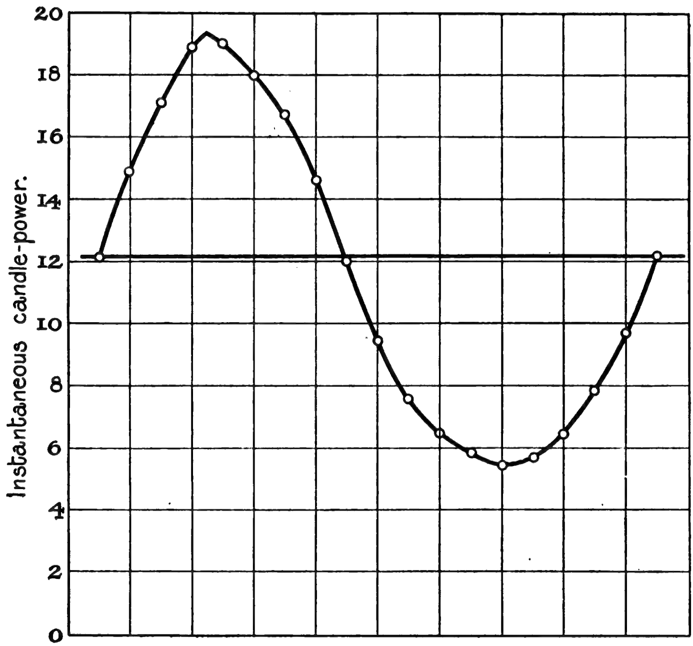

FIG. 3.

This must give rise to a difference between the current and E.M.F. waves.

These were plotted out at 25 periods for the 0·1 ampere lamp and are given in Fig. 4. In order to secure that the conditions should be unaffected by change of apparatus when changing over from plotting the current to plotting the E.M.F., the latter wave was obtained by plotting the current wave through a Eureka resistance taking the same current as the lamp and substituted for it.

The E.M.F. wave has an amplitude factor of 1·435, the current wave, 1·430. The mean ordinate is 0·901 of the R.M.S. value for E.M.F. and 0·905 for current.

The two waves are coincident at zero, but the current wave leads by 4 degrees at the higher values. The average lead is about 2 degrees and the effective lead is about 3 degrees, as drawn.

The effective lead was further measured as follows :—

The lamp was connected in series with a wattmeter whose shunt coil was energised by a quadrature winding on the alternator. A Eureka resistance taking exactly the same current was then substituted

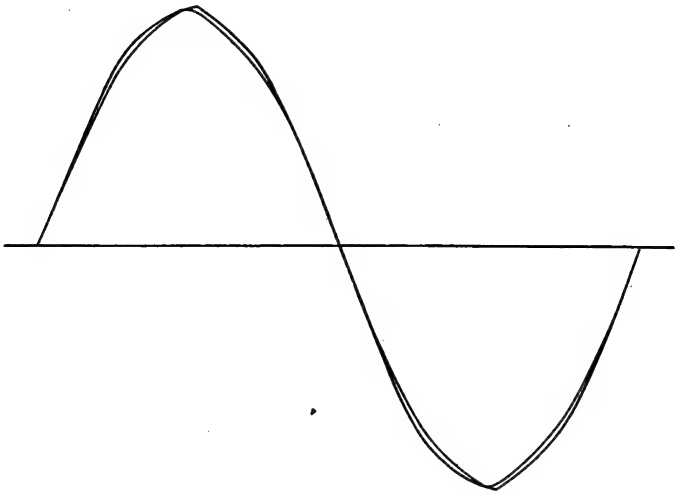

FIG. 4.

for the lamp and a change in the reading of the wattmeter was at once noted. This change corresponded with a change of phase angle of just 2 degrees. So the effective lead of the current through the lamp is 2, not 3, degrees, and the difference shown in the waves is therefore somewhat exaggerated.

It is somewhat interesting to find that tungsten lamps take what practically amounts to a leading current. Carbon lamps, on the other hand, having a negative temperature coefficient, should take a slightly lagging current.

JOURNAL

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Proceedings of the Five Hundred and Thirty-seventh Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, 21st March, 1912—Dr. S. Z. DE FERRANTI, President, in the chair.

The minutes of the Ordinary General Meeting, held on 14th March, 1912, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council:—

TRANSFERS.

From the class of Associate Members to that of Members:—

Harold H. Broughton.
William Cotsworth.
James Fraser Lister.
Edwin Safford Reid.
Professor David Robertson.
Oliver Cromwell Spurling.
Captain R. ff. Willis.

From the class of Associates to that of Members:—

Hedley J. Thomson.
Walter R. Underhill.

From the class of Associates to that of Associate Members:—

Alexander Walker Brown.
William Bunn.
Charles Mark Davis.
Captain Ralph E. Stace.

From the class of Students to that of Associate Members :—

Gerald Sidney Cattell.	Alfred H. Huddart.
Alick Maling.	Leonard S. Payne.
Harold Walter Purle.	William Robert Steele.
Khurshed P. Framjee.	Claude F. D. Suggate.
George Stanley Helme.	Robert Oliver Udall.

From the class of Students to that of Associates :—

Alexander McWilliam.

The evening was occupied in a discussion on "The Causes preventing the more General Use of Electricity for Domestic Purposes."

Proceedings of the Five Hundred and Thirty-eighth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, 28th March, 1912—Mr. J. F. C. Snell, Vice-President, in the chair.

The Chairman: It is with regret that I have to announce the death of an old and distinguished Honorary Member of our Institution, Professor Antonio Pacinotti. To every student the name of Pacinotti will be well known, and in order to express your regret at his death I ask you to rise.

The resolution was carried in silence, all present standing.

The minutes of the Ordinary General Meeting, held on 21st March, 1912, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council:—

TRANSFERS.

From the class of Associate Members to that of Members—

Percy M. Williamson.

From the class of Associates to that of Members:—

John Kendall Stothert.

From the class of Students to that of Associate Members:—

Frank Barlow.
Emil A. Biedermann.
Morgan Howell Rees.
Gerald M. S. Sichel.
Edward John Stevens.

Messrs. B. B. Heaviside and H. E. Trent were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected:—

ELECTIONS.

As Member.

Arthur Handley.

ELECTIONS (*continued*).

As Associate Members.

Francis Douglas Brown.
Sarat Kumar Dutta.
William Henry Gatley.
Lawrence A. Gomersall.
Charles William Holman.
Albert Jacques Huber.
John Rudolph Kingston.
Norman Cameron Rowan.
Thomas Frederick G. Shephard.
William Francis Stephenson.
Allan Brewer Wearing.
Sydney Webster.
William John H. Wood.

As Associates.

Andrew Henry Beatty.
Emile Brooks.

As Students.

Reginald Sidney H. Boulding.
Reginald William Brenegan.
Lewis Burn.
Charles Mark Denny.
Robert Edward S. Fisher.
James Aitken Kinnaird.
Herbert Henry Leys.
Frederick John Libby.
John Watt Mowat.
Edward Thomas.
William Arvon Wales.
Hugh Henry W. Warren.

A paper by J. A. Fleming, M.A., D.Sc., F.R.S., Member, and G. B. Dyke, B.Sc., Associate Member, entitled "The Power Factor and Conductivity of Dielectrics when Tested with Alternating Electric Currents of Telephonic Frequency at various Temperatures" (see page 323), was read and discussed.

ON THE POWER FACTOR AND CONDUCTIVITY OF DIELECTRICS WHEN TESTED WITH ALTERNATING ELECTRIC CURRENTS OF TELEPHONIC FREQUENCY AT VARIOUS TEMPERATURES.

By J. A. FLEMING, M.A., D.Sc., F.R.S., Member, and G. B. DYKE, B.Sc., Associate Member.

(*Paper received 15th January, received in final form 2nd May, and read before* THE INSTITUTION *28th March*, 1912.)

PART I.—THEORETICAL.

By J. A. FLEMING.

Many very careful researches have already been made upon the energy losses in dielectrics when acted upon by alternating electric force. It would occupy too much space to present even an epitome of previous work.* The subject nevertheless is far from being exhausted. Whilst great attention has been given to the study of the processes by which electricity is moved through metals, electrolytes, and gases, there are still important matters connected with the dissipation of energy in, and the conductivity of, dielectrics which require elucidation. The topics in which electrical engineers are naturally most interested are the energy losses in the dielectrics of cables and condensers when subjected to alternating electromotive force of low, medium, or high frequency, and of various voltages and wave-form. The importance of this in the cases of power transmission as well as telephony is well understood.

In the present paper we concern ourselves with only one department of the subject, viz., the power factor and conductance of dielectrics under alternating electromotive force of low voltage, pure sine wave-form, and of frequencies between 900 and 5,000 p.p.s., as this has

* This has been rendered the less necessary by the long list of references to original papers on dielectrics at the end of Mr. E. H. Rayner's paper on "High-voltage Tests and Energy Losses in Insulating Materials" recently read before this Institution. Also in *Winkelmann's Handbuch der Physik*, 2nd ed., vol. 4, part i., p. 77, will be found a section by L. Graetz on the properties of dielectrics, which gives a most complete account of the theory and experimental results obtained up to 1902 and an extensive list of references to original papers. Another long list of references to papers on dielectric phenomena is given by E. von Schweidler in the *Annalen der Physik*, vol. 24, p. 766, 1907. References to many papers on dielectric constants are to be found in Landolt and Börnstein's *Physikalische-Chemische Tabellen*, 1st ed., p. 525; 3rd ed., p. 774, 1905.

a close connection with practical telephony. The energy loss at high voltages and low frequency (700 to 20,000 volts and 50 to 100 p.p.s.) has been studied by B. Monasch, and quite recently by E. H. Rayner.*

It has long been known that the conductivity of certain dielectrics for alternating currents of telephonic frequency is much greater than for direct or unidirectional currents, and the principal object of our work was to examine this alternating conductance (denoted by S) and the capacity C, as well as the ratio S/C for condensers and cables made with various dielectrics and tested at different temperatures and frequencies within the range of telephonic work.

Telephonists are well aware of the great effect which the ratio of the leakance of a line to its capacity per mile exercises upon the attenuation constant, and therefore on the speech-transmitting qualities, especially in the case of highly inductive or loaded lines. In these cases if S denotes the alternating-current dielectric conductance or leakance per mile and C the capacity per mile, the ratio S/C (denoted by s) is an important quantity.

This same ratio s concerns us in the case of condensers having dielectric conductance or leakance which are operated with simple harmonic alternating electromotive force of maximum value V and frequency $n = p/2\pi$. If a condenser or cable of capacity C has such a voltage applied to it, it creates a dielectric current $\mathrm{C}p\mathrm{V}$ nearly in quadrature with the impressed voltage, and also there is, or may be, a power absorption proportional, as shown by all experiments, to the square of the impressed voltage.† This indicates that there is a current SV in step with the voltage. Hence, the power factor of the condenser is given by the expression $s/\sqrt{p^2 + s^2}$, but for small power factors is sufficiently nearly expressed by s/p or by $\mathrm{S/C}p$.

It can easily be shown that for a loaded telephone cable operated with alternating currents of frequency $p/2\pi$ having conductor resistance R, conductor reactance $\mathrm{L}p$, dielectric leakance S, and dielectric admittance $\mathrm{C}p$, if $\mathrm{R/L}p$ and $\mathrm{S/C}p$ are small quantities, the attenuation constant a is approximately given by the expression—

$$a = \tfrac{1}{2}\left(\frac{\mathrm{R}}{\mathrm{L}} + \frac{\mathrm{S}}{\mathrm{C}}\right)\sqrt{\mathrm{CL}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If we denote the ratio R/L by r, and S/C by s, we can write the expression for the attenuation constant of a cable having a capacity C and inductance L per unit of length in the form—

$$a = \left(\frac{r+s}{2}\right)\sqrt{\mathrm{CL}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

* See Monasch on the "Energy Loss in Dielectrics in Alternating Electric Fields," *Annalen der Physik*, vol. 22, p. 905, 1907, and *Science Abstracts*, vol. 10, A, No. 1084, 1907; and E. H. Rayner, "High-voltage Tests and Energy Losses in Insulating Materials," *Journal of the Institution of Electrical Engineers*, vol. 49, p. 3, 1912.

† See B. Monasch, *Annalen der Physik*, vol. 22, p. 905, 1907, and *Science Abstracts*, vol. 10, A, No. 1084, 1907. Monasch asserts that the square law is accurately true except when the voltage is sufficiently high to cause brush discharges.

It may be noted in passing that Oliver Heaviside's condition for the absence of distortion in cables is expressed by the equation—

$$r - s = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

In the case of oscillations of a condenser having dielectric conductance S connected in series with an inductive circuit having resistance R, it can also be proved that the frequency of the oscillations is given by the formula—

$$n = \frac{1}{2\pi}\sqrt{\frac{1}{CL} - \left(\frac{r-s}{2}\right)^2},$$

where C is the condenser capacity, and L the inductance of the circuit, and r and s denote the ratios R/L and S/C. The damping factor for the circuit is $\epsilon^{-\frac{r+s}{2}t}$, and the decrement per period of the oscillations is $(r+s)/2n$.

These quantities r and s are of the dimensions of the reciprocal of a time, and s moreover is independent of the geometrical form of the condenser or cable dielectric, and is a specific constant for the material such that $S/C = 4\pi\sigma/k$, where σ denotes specific conductivity and k the dielectric constant, provided that we may assume the dielectric conductivity obeys Ohm's law. This assumption is certainly not valid as a general rule, but if made the theorem can be proved as follows:—

Suppose a conductor of any shape is immersed in a dielectric of specific conductivity σ and dielectric constant k, and that the dielectric is surrounded by another conductor kept at zero potential. Let V be the potential of the inner conductor and E the normal electric force at any element ds of the surface. Then if dn is an element of length, measured outwards along the normal, we have $-\frac{dV}{dn} = E$. Also if Q is the total charge of the conductor, then since Q is equal to the surface integral of the normal displacement or electric flux, and $Q = CV$ where C is the capacity of the body, we have—

$$\frac{k}{4\pi}\int E\,ds = Q = CV.$$

Again, if I is the current density of the current flowing into and through the dielectric and σ is the conductivity, provided σ is independent of E we have—

$$I = -\frac{dV}{dn}\sigma = \sigma E.$$

Hence—

$$\frac{k}{4\pi\sigma}\int I\,ds = Q = VC.$$

But if the total conductivity of the dielectric is S, then—

$$SV = \int I\,ds,$$

and therefore we have—

$$4\pi\sigma/k = S/C.$$

Accordingly $S/C = s$ is independent of the shape of the dielectric.

In the experimental part of this paper it will be shown that when employing alternating currents the effective dielectric conductance S is a function of the frequency, and is much greater than the steady current conductance measured in the ordinary way.

The reason for this must be that there are then additional sources of internal dissipation of energy in the dielectric. One conclusion which is evident, both from the experiments recorded in this paper and from those of previous workers, is that any moisture present in the dielectric immensely increases this alternating-current dielectric loss. But apart from this it appears that the energy loss can be divided into two parts. One part which results from a conductivity independent of the frequency which is possibly electrolytic in nature, and another part which results from a conductivity very nearly proportional to the frequency, at least within the limits of voltage employed in the experiments here described which possibly may be connected with a dielectric energy loss analogous to that which we call the hysteretic loss in iron under alternating magnetisation. It is this total alternating-current conductivity and its ratio to the capacity which especially concerns us in the case of cables and condensers used in telephony.

It is curious that cable manufacturers continue to pay such great attention to the so-called insulation resistance (I.R.) measured by applying a steady or direct-current voltage to the cable and then stating the I.R. as so many megohms per mile after 1 minute's electrification. Except as a rough test of dielectric strength and means of revealing defects of manufacture the above measurement has very little, if any, scientific value. Even in the case of cables or insulated wires to be used with direct currents it is no indication of the current which will flow through the dielectric after the lapse of hours or days. In the case of insulated cables to be used with alternating voltage, and especially high-frequency voltage, such as telephone cables, this direct-current insulation resistance has little or no importance.

The quantities which then have real significance are the alternating-current conductance S for a stated temperature and frequency, the ratio $S/C = s$, and the ratio $S/Cp = s/p$ (which when small is nearly the power factor), and the quantity usually called the admittance $\sqrt{S^2 + C^2p^2}$.

In all these expressions when they occur in formulæ concerned with telephonic transmission and high-frequency currents the symbol S is *not* to be taken as equivalent to the reciprocal of the insulation resistance measured with direct currents, nor is the C the steady or direct-current capacity, but they are quantities only to be obtained by special measurements.

The two quantities with which we are concerned in this paper, viz., the capacity and dielectric conductance of condensers or cables for

simple harmonic currents, may be numerically defined respectively, as the number by which the mean-square voltage or mean-square terminal potential difference (P.D.) must be multiplied to give the maximum energy storage in each half period; and as the number by which the same quantity must be multiplied to give the mean power absorption in the dielectric.

The capacity and conductance for direct currents may be defined in a somewhat similar manner, since at any one instant the energy being spent upon the dielectric is divisible into two parts, one part which is ultimately recoverable and is due to the capacity, and the other part, which is non-recoverable, or is being dissipated as heat, which is due to the conductance.

Assuming we have a condenser constructed with such a dielectric as gutta-percha we find that when a steady constant E.M.F. is applied to it there is at first a current into the condenser which rises very quickly to a maximum value and then dies gradually away or decreases to a constant minimum.

In the same manner on discharge a large current comes out for a short time and then tails away rapidly, but a small current continues to come out for a long time.

This process is generally referred to as the *absorption* of the dielectric, although the term is very misleading. In a so-called perfect or non-absorptive condenser the charge and discharge would be completed in an infinitely short time. It is sometimes stated that we can imitate the behaviour of any condenser as regards its mode of charge and discharge due to absorption by substituting for it a perfect condenser having a certain resistance placed in series with it. This is made the foundation of certain bridge methods for comparing capacities. The statement is, however, true only within certain limitations.

If C is the capacity of a perfect condenser in series with a resistance R, and if V is a constant electromotive force applied to the condenser and resistance in series, and if v is the potential difference of the condenser plates at any time t after applying the E.M.F., then we have—

$$\frac{V - v}{R} = C\frac{dv}{dt} \quad \dots\dots\dots \quad (4)$$

which integrated gives—

$$v = V\left(1 - \varepsilon^{-\frac{t}{CR}}\right) \quad \dots\dots\dots \quad (5)$$

Hence if q is the quantity of electricity in the condenser at the time t, and if Q is the final charge, we have—

$$q = Q\left(1 - \varepsilon^{-\frac{t}{CR}}\right) \quad \dots\dots\dots \quad (6)$$

and the current i at the same instant flowing into the condenser is therefore—

$$i=\frac{V}{R}\varepsilon^{-\frac{t}{CR}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Experiment shows that the charge and discharge current of a condenser formed with most solid dielectrics does not obey any such simple exponential law, and the charge at any time t after applying a steady E.M.F. cannot be represented, generally speaking, by an equation of the form of (6), at least if the time is not very short. The measurement of the dielectric constant of dielectrics corresponding to various times of charging made, for instance, by the method used by Professor Thornton,* shows that the charge taken up by a condenser under constant E.M.F. first rises very suddenly, then increases

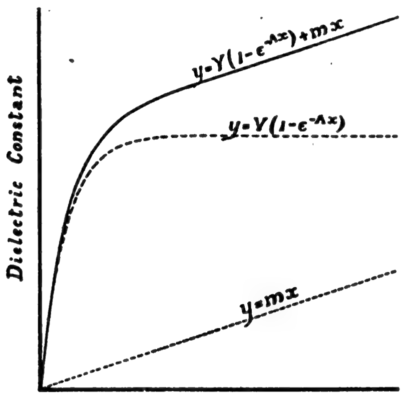


FIG. 1.

more slowly almost in accordance with a straight line law, and then finally approaches asymptotically a limiting value. This increase of charge with time may in general be represented by such a curve as is shown in Fig. 1. Of these three stages the second stage or slow increase according to a linear time function is called the absorption. A curve of this kind, however, can be imitated almost exactly, as far as regards the first two stages, by superimposing a curve represented by an equation of the form—

$$y=Y(1-\varepsilon^{-Ax})$$

on a straight line—

$$y=mx+C.$$

* W. M. Thornton, "The Polarisation of Dielectrics in a Steady Field of Force," *Proceedings of the Physical Society*, vol. 22, p. 186, 1910; *Philosophical Magazine*, vol. 19, p. 390, 1910; and *Science Abstracts*, vol. 13, A, No. 612, 1910. In this paper a diagram is given showing by curves the manner in which the dielectric constant of various insulators increases with time of application of the electric force.

Hence we may say that the charge q in a condenser at any time t not very long after applying a constant E.M.F. is given very nearly by an expression of the form—

$$q = Q_1(1 - \varepsilon^{-A_1 t}) + Q_2 A_2 t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

or if $A_2 t$ is a small quantity, by—

$$q = Q_1(1 - \varepsilon^{-A_1 t}) + Q_2(1 - \varepsilon^{-A_2 t}) \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where $Q_1 + Q_2$ is equal to Q or to the full final charge.

An equation of the form (8) or (9) can be made to fit by a suitable selection of the constants, a curve such as that in Fig. 1 which rises quickly to a certain ordinate and then slopes upward almost in a straight line, but finally tends to a limiting ordinate.

If, then, we take two non-absorptive condensers of capacities C_1 and C_2 and place in series with them inductionless resistances R_1 and R_2,

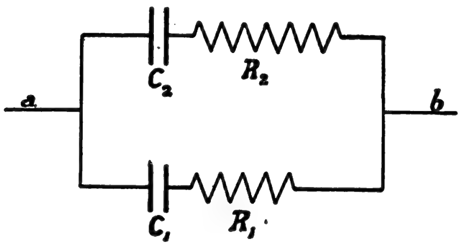


FIG. 2.

and connect the two in parallel as in Fig. 2, and if we adjust the capacities and resistances so that the product of capacity and resistance ($C_1 R_1$), for one is much smaller than the product ($C_2 R_2$) for the other, we shall have an electrical arrangement which can be adjusted to imitate more closely the behaviour of a single condenser having absorption. For if we apply to the above system a constant E.M.F. equal to V, then for one condenser the current i into it at any instant t in accordance with equation (7) is given by—

$$i_1 = \frac{V}{R_1}\varepsilon^{-\frac{t}{C_1 R_1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10$$

and that into the other by—

$$i_2 = \frac{V}{R_2}\varepsilon^{-\frac{t}{C_2 R_2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Hence the quantity q which has flowed into the whole system is given by—

$$\int (i_1 + i_2)\, dt$$

or by—

$$q = \text{constant} - Q_1 \epsilon^{-\frac{t}{C_1 R_1}} - Q_2 \epsilon^{-\frac{t}{C_2 R_2}} \quad . \quad . \quad . \quad . \quad (12)$$

where—

$$Q_1 = C_1 V$$

and—

$$Q_2 = C_2 V,$$

and the constant of integration is the total final charge Q. Accordingly we have—

$$Q - q = Q_1 \epsilon^{-\frac{t}{C_1 R_1}} + Q_2 \epsilon^{-\frac{t}{C_2 R_2}} \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and—

$$Q = Q_1 + Q_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Now equation (13) is identical with (9). Hence if R_2 is a large resistance and R_1 a small resistance, so that $C_1 R_1$ is small compared with $C_2 R_2$, it is easily seen that the quantity which flows into the combined condenser system will first increase suddenly by an amount Q_1 and will then increase slowly according to a simple linear law expressed by $Q_1 + Q_2 t/C_2 R_2$, and finally tend to a limit $Q = Q_1 + Q_2$, just as experiment shows to be the case. Accordingly, although we cannot imitate electrically an absorptive condenser by a single non-absorptive condenser placed in series with a resistance, we can imitate it far better by a pair of non-absorptive condensers, one having a high resistance in series with it and the other a low resistance, the two series being joined in parallel.

But it is interesting to notice that such a system not only imitates the absorption, but imitates also the so-called residual charge effect of a condenser with a solid dielectric. As is well known, a condenser made with glass, gutta-percha, or, better still, celluloid, as dielectric when charged, allowed to stand insulated, and then discharged and allowed to stand again, soon exhibits a revived charge of the same sign called the residual charge. Also when the process is repeated a second or third time other residual charges can be obtained.

This effect was investigated by Faraday,* who noticed that it was well shown by a spermaceti condenser, and forty years later it was examined by Dr. J. Hopkinson,† who discovered that the appearance of the residual charge was promoted by tapping the dielectric.

Maxwell ‡ has proved that a compound dielectric built up of layers or laminæ of different non-absorptive dielectrics should exhibit both absorption and residual charge effect, provided these laminæ each have dielectric constant k and dielectric conductance σ such that the ratio σ/k is different for each lamina, although every lamina by itself does not exhibit either absorption or residual charge.

* M. Faraday, "Experimental Researches," vol. 1, series xi., p. 386, § 1232.

† J. Hopkinson, "On the Residual Charge of the Leyden Jar," *Philosophical Transactions*, vol. 167, p. 599, 1877.

‡ J. C. Maxwell, "A Treatise on Electricity and Magnetism," 2nd ed., vol. 1, chap. x., p. 412.

Maxwell's argument on this subject in his book extends over three pages of mathematical discussion, but the result is as follows:—

Suppose the dielectric of a plate condenser with terminal plates each of unit area to be built up of laminæ of different dielectrics of thickness l, conductivity σ, dielectric constant k, and for each sheet let $4\pi\sigma/k = s$ have a different value. Suppose this plate condenser charged to a terminal potential difference equal to V and then discharged and insulated. After a time t reckoned from the instant of discharge, the terminal plates will have risen again to a potential difference equal to v, and Maxwell's formula for v is equivalent in our notation to—

$$v = \mathrm{V}\,\Sigma\left(\frac{l}{\sigma}(\mathrm{S} - s\,\mathrm{C})\,\varepsilon^{-st}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

If $t = 0$, then $\frac{l}{\sigma}\left(\mathrm{S} - s\mathrm{C}\right)$ is easily shown to be identically zero. Also if s is the same for each lamina, then ε^{-st} can be put outside the summation sign and the value of v is also zero. If, however, s is different for each lamina, then v or the terminal potential difference of the compound condenser increases with t up to a certain value of t and then dies away again. This constitutes the reappearing residual charge.

A justification for the hypothesis that the residual charge effect depends upon a want of homogeneity in the structure of the dielectric in that the value of $4\pi\sigma/k$ is different in different parts is asserted to be found in the fact that most dielectrics exhibiting it are complex substances such as glass, indiarubber, gutta-percha, etc.

On the other hand, it has been found that an exponential formula such as (15) does not agree with observation. Professor F. T. Trouton and Mr. Russ have shown that the recovered charge can be much more nearly represented by a logarithmic formula—

$$q = a\log(t + b) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where q is the charge which has reappeared at a time t after the discharge of the condenser, and a and b are constants.* The rate at which the charge reappears is therefore capable of being expressed by a hyperbolic formula—

$$i = \frac{d}{t + b} - c \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

where d, b, and c are constants. The measured values of the rate of recovery of the charge were found by Trouton and Russ to fit well on to a hyperbola.

The well-known analogous stress-strain phenomena in viscous elastic solids such as glass are capable of being represented by similar formulæ, but beyond establishing the fact that there is an

* F. T. Trouton and S. Russ, "The Rate of Recovery of Residual Charge in Electric Condensers," *Proceedings of the Physical Society*, vol. 20, p. 551, 1907; *Philosophical Magazine*, vol. 13, p. 578, 1907; and *Science Abstracts*, vol. 10, A, No. 1058, 1907.

analogy between the two effects the mathematical theories do not help us much to discriminate between different physical hypotheses framed to enable us to visualise the molecular processes at work.

On the other hand, it may be noticed that the double condenser-resistance system suggested above as a means of representing the phenomenon of absorption imitates at least qualitatively the residual charge effect, provided that the value of the product $C_1 R_1$ for one series is different from the product $C_2 R_2$ of the other. For if this is the case, and if we assume the system charged with a constant E.M.F. V, and then discharged, the two condensers contribute unequally to this initial discharge current, and hence when insulated and allowed to stand the condenser for which the product $C R$ is the smallest fills up again with charge drawn from the other condenser, and therefore after a time will give another discharge in the same direction, and also in like manner a series of residual discharges can be obtained. If, therefore, we take two non-absorptive condensers—say, air condensers or oil condensers—and join one of them in series with a very high resistance and one in series with a very low resistance and place the two series in parallel, we can produce a compound condenser which imitates most perfectly all the phenomena exhibited by a condenser made with such a dielectric as glass or celluloid possessing absorption and residual charge. But more, such an arrangement will possess the quality that, whilst it has no permanent conductivity for direct currents, it has yet a true conductivity and energy dissipating power for alternating currents. This quality is very marked in certain dielectrics as, for instance, gutta-percha. If a gutta-percha insulated cable is tested with continuous current, its final insulation is found to be extremely high, something of the order of a hundred million megohms per centimetre cube. It has, however, as shown in this paper, an immensely greater conductivity for alternating currents of telephonic frequency. Suppose a resistance R is placed in series with a condenser of capacity C and an alternating E.M.F. represented by $V \sin pt$ is applied to the series. Then the differential equation giving the charge q at any instant is—

$$R\frac{dq}{dt} + \frac{q}{C} = V \sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Hence integrating and neglecting the auxiliary function we have—

$$q = \frac{CV}{\sqrt{1 + C^2 R^2 p^2}} \sin (pt - \theta) \quad . \quad . \quad . \quad . \quad . \quad (19)$$

and the current is given by—

$$i = \frac{dq}{dt} = \frac{CVp}{\sqrt{1 + C^2 R^2 p^2}} \cos (pt - \theta) \quad . \quad . \quad . \quad . \quad (20)$$

where $\theta = \tan^{-1} CRp$, and therefore—

$$\sin \theta = \frac{CRp}{\sqrt{1 + C^2 R^2 p^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Therefore the mean power wasted in the resistance is—

$$W = \frac{C^2 R^2 p^2}{1 + C^2 R^2 p^2} \frac{1}{R} \frac{V^2}{2} = \sin^2\theta \frac{1}{R} \frac{V^2}{2} \quad . \quad . \quad . \quad . \quad (22)$$

The equivalent conductance of the system is therefore—

$$S \sin^2\theta,$$

where—

$$S = 1/R.$$

Hence the pair of condensers each in series with a resistance and the two series in parallel will have an alternating conductance represented by—

$$S = \frac{p^2 S_1}{s_1^2 + p^2} + \frac{p^2 S_2}{s_2^2 + p^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

where S_1 and S_2 are respectively the conductances of the resistances R_1 and R_2, and s_1 and s_2 stand for the quantities $1/C_1 R_1$ and $1/C_2 R_2$.

The system will, however, have no conductivity for direct currents.

If the ratio s is very small for one condenser and large for the other, the alternating-current conductance would be a function of the frequency of the form—

$$S = A + B n^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

It will be proved, however, in the second part of this paper that in by far the largest number of cases the alternating-current (A.C.) conductance of a dielectric is a simple linear function of the frequency of the form—

$$S = A + B n \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Hence it is clear that we cannot explain alternating-current conductance merely by hypothecating in the dielectric a resistance of the nature of a metallic resistance. We must assume that some form of energy dissipation exists in the dielectric which is proportional to the mean-square value of the impressed electric force and to the frequency of the alternations, whilst superimposed on this we have also a conductance of the metallic or electrolytic type.

The view that we have two different kinds of conductivity simultaneously present in a dielectric receives support from the recent interesting experiments of Jaffé and of Hodgson.* Starting from the observation made originally by P. Curie that the conductivity of solid and liquid insulators is increased by exposing them to radium radiation, Jaffé found that the current through a dielectric exposed to radioactive bodies may be divided into two parts—one which obeys Ohm's law, and an ionisation or convection current which does not obey it,

* G. Jaffé, "The Ionisation of Liquid Dielectrics by Radium Rays," *Annalen der Physik*, vol. 25, p. 257, 1908; and *Science Abstracts*, vol. 11, A, No. 439, 1908; also H. Hodgson, "The Conductivity of Dielectrics under the Action of Radium Rays," *Philosophical Magazine*, vol. 18, p. 252, 1909; and *Science Abstracts*, vol. 12, A, No. 1600, 1909; see also G. W de Tunzelmann, "A Treatise on Electrical Theory," p. 110.

at least when the electric force in the dielectric exceeds a certain limit. The current obeying Ohm's law is probably electrolytic in nature, and according to Jaffé is chiefly due to impurities. The ionisation current is a convection current due to the presence of mobile ions or electrons as in the case of gaseous conduction, and it has a saturation value. If, in addition to this, there is any true direct-current conduction, there must be a small number of free electrons present. As regards direct-current conduction, all good dielectrics have exceedingly high resistivity of the order of a hundred million megohms per centimetre cube. By most careful purification of the dielectric, that part of the conductivity which obeys Ohm's law can be almost removed. On the other hand, there remains a true alternating-current conductivity, which is nearly proportional to the frequency and increases very rapidly with temperature in most cases. The interesting question then arises, What is the explanation of this last conductivity?

Since the electron theory of electricity has provided an hypothesis from which we can logically deduce the chief facts of metallic and electrolytic conduction, it is natural to ask of it a similar service for dielectric conduction.

Metallic conduction is explained on one theory by the assumption that in the interstices of the metallic atoms of a conductor there are free electrons in the act of passing from one atom to another. If an external electric force acts on these free electrons in one direction it causes a unidirectional drift. The current in the conductor is measured by the product of the total number of electrons per unit volume, the electronic charge, and the mean drift velocity, or by $N e u$, where N is the number of electrons per cubic centimetre, e is the electronic charge, and u the drift velocity. If E is the external electric force, the acceleration of the electron in its direction is $e\,E/m$, where m is the mass of the electron, and hence the mean drift velocity is $e\,E\,t/2\,m$, where t is the time of mean free path. If l is the length of the mean free path of the electron, and v the mean electronic velocity, we have the value of the current given by the expression—

$$I = \frac{N e^2 l}{2 m v} E.$$

If, then, the mean velocity v is not sensibly changed by the action of the external force E, the above expression is a statement of Ohm's law, and the direct-current conductivity is constant and expressed by $N e^2 l/2 m v$.

In most dielectrics at ordinary temperatures the direct-current conductivity is very small. Hence the free electrons must be very few in number.

The characteristic quality of a dielectric is that we can produce in it an electric displacement proportional to the impressed force, which, however, is of a purely elastic type, and vanishes when the force is removed.

This must be accounted for by the presence of displaceable ions which elastically resist displacement with a force proportional to the displacement.

Consider a particle subject to a force proportional to the displacement restoring it to its original position, let x be the displacement and μx the restoring force, then $\frac{1}{2}\mu x^2$ is the work done in displacing it. If the displacement is created in a time T/4, then the rate of doing the work is $2\mu n x^2$ where $n = 1/T$. If f is the force, then the mean power expended is $\frac{2n}{\mu}f^2$.

Suppose, then, that an electron is held tethered to one spot by a force which is proportional to the displacement when the electron is disturbed. If an external alternating electric force acts on it, periodic displacements of the electron would be created, but in any time, long compared with that of the periodic time, no power on the whole would be expended, since the work done in creating a displacement is given back again when the displacement vanishes, provided these forced oscillations have a periodic time which is large compared with the natural time period of oscillation of the electron. If this is the case the movement of the electron would be entirely controlled by the variation of the external electric force just as the motion of an oscillograph wire or needle is controlled by the slower period alternating electric current acting on it. Also if these forced oscillations are relatively slow the loss of energy by electric radiation will be very small. Suppose, however, that the constraint on the electron is of such a nature that when it is displaced beyond a certain point, it falls over into a new position of equilibrium. The work expended in creating this displacement would be dissipated as electric radiation in the rapid oscillations which the electron would execute about the new position of equilibrium. If the process of carrying the electron backwards and forwards between the stable positions is repeated n times per second, then the power expended would be proportional to the square of the impressed force, and to the frequency n of the forced oscillations, or to $B n V^2$. In this case, then, the equivalent or alternating conductivity would be proportional to the frequency.

We can then account for many of the observed facts connected with dielectrics on the following hypothesis: Let it be assumed that in a dielectric there are three classes of displaceable electrons or ions: (1) Electrons which under the action of a unidirectional or alternating impressed electric force are elastically displaced from a position of equilibrium. If the force is alternating no power would on the average be expended in maintaining these forced oscillations. The flux of electrons thus taking place across any section of the dielectric constitutes the true capacity current, and is proportional to the frequency and to the impressed force. If the periodic time of these forced oscillations is large compared with the time of free vibration of the electron when left to itself to execute free vibrations, then but little energy will be lost by radiation. (2) Other electrons or ions must be

present which can be displaced from a position of equilibrium, but with increasing displacement are brought into an unstable position from which they fall freely into a new position of equilibrium and dissipate the energy expended in displacing them in the form of electromagnetic waves due to the rapid free oscillations about the new position of equilibrium. If this process is repeated first in one direction and then in another we have a flux of electrons across any section of the circuit. The alternating current so produced is proportional to the frequency of movement from one stable position to the other. (3) There must be a relatively very small number of free electrons which contribute to produce the constant or direct-current conductivity.

It follows from these assumptions that a dielectric must possess dielectric constant k and true capacity, and also an alternating-current conductivity σ approximately of the type $\sigma = a + b\,n$, where a and b are constants at any given temperature, and n is the frequency of the impressed force. Therefore S/Cp will not be constant unless the quantity a in the above expression for the conductivity is very small. If it should happen that the quantity a is small compared with $b\,n$ then the quantity S/Cp will be independent of frequency.

To account, however, for absorption and the residual charge effect we have to assume that there is some yielding of the point of support to which the elastically displaceable electrons which produce capacity are tethered. This may best be seen by the help of a mechanical analogue.

Suppose we have an endless tube filled with some liquid, say oil (see Fig. 3). At one point in the tube let there be a piston M which can be moved by an external applied pressure. This is equivalent to an electromotive force. Let the tube have a by-pass with stop-cock S in it shunted around this piston. Let there be also a number of frictionless pistons, P_1, P_2, P_3, etc., in the tube, each of which is attached to a spiral spring, the other end of the spring being fastened to rings C_1, C_2, C_3, etc., fitting into the tube, but which ring can in some cases slip with friction in the tube so as to displace the point of attachment of the frictionless piston.

Suppose, then, that we apply a constant pressure to the main piston, the by-pass stop-cock being closed. The liquid would be forced round the tube as far as the elastic constraint of the frictionless pistons will permit. This is equivalent to electromotive force acting on a condenser, and the pistons represent the elastically displaceable electrons. Suppose the applied pressure removed, the pistons will spring back and reverse the flow of the liquid. This corresponds to the discharge current of the condenser. If, however, some of the points of attachment of the controlling springs slip gradually along the tube, then the first sudden displacement of the other pistons or of the liquid will be followed by a still further slow displacement under the action of the constant impressed force. This corresponds to the absorption current of the condenser. Again, when we release the applied pressure, there will be a sudden springing back of the pistons and of the liquid

followed by a still further slow movement as the point of attachment of certain of the pistons gradually slips along the tube. This corresponds to the subsequent small outflow of current after the first discharge from any condenser having absorption.

Also, the same model will illustrate the residual charge effect. For if we suppose an impressed force applied to the main piston so as to create a displacement of the liquid in the tube, and if we assume that the stop-cock is shut we have a state analogous to that of a condenser which has been charged and then insulated. Imagine, then, that the points of attachment of certain of the pistons slip so that these pistons cease to be under elastic constraint. If, then, we open the stop-cock and let the liquid flow, those pistons, the supports of which have not yielded, will force the liquid back, but will put a reverse displacement

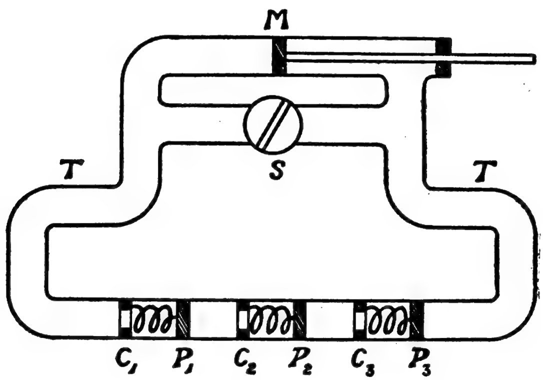


FIG. 3.

on the pistons whose supports have slipped. Suppose, then, we shut the stop-cock and wait again, a second slipping of the same points of support will take place, and, on opening the stop-cock a second time, a still further flow back of the liquid will take place in the same direction as the first return. This is quite analogous to the residual charge effect in condensers. Hence we see that both absorption and residual charge effect may arise from the same cause, viz., some slipping of the point of attachment of the constraint of the elastically displaceable ions.*

In the dielectric, therefore, we may assume that the point to which the elastically displaceable electrons are constrained, is not a fixed point in space, but is some part of an atomic or molecular structure or ion which slowly yields under the applied electromotive force, and that this yielding takes place more in some parts than in others in the dielectric. We should expect to find it therefore exhibited in dielectrics of complex chemical composition.

* A somewhat similar mechanical model illustrating dielectric phenomena was described by Sir Oliver Lodge in 1876. See *Philosophical Magazine*, vol. 2, p. 524, 1876.

As a matter of fact, the dielectrics like glass, celluloid, indiarubber, gutta-percha, etc. which exhibit the phenomena of absorption and residual charge are composed of mixtures of various substances. Before, however, we indulge in further speculation as to the mechanism of these dielectric effects it will be best to describe the experiments we have made and the results obtained.

PART II.—PRACTICAL AND EXPERIMENTAL.

By J. A. FLEMING and G. B. DYKE.

The experiments here described were directed in the first place to determine the value of the apparent conductance S and the capacity C for alternating electromotive forces of simple sine-form and frequencies lying between 800 and 5,000, viz., the telephonic range, for various dielectrics taken at stated temperatures. For this purpose we had to develop a method capable of being applied to small condensers or short lengths of cable, these condensers being made up with different dielectrics, and in such form that they could be submitted to a wide range of temperature change.

As we can generally bring theory and experiment into comparison only in those cases in which we employ simple harmonic currents and voltages, a preliminary problem to which we directed attention was the provision of the periodic electromotive forces of required frequency, wave-form, and value.

We possess in the Pender Electrical Laboratory, at University College, London, an alternator built by Messrs. Crompton & Co., of Chelmsford, the normal frequency of which is about 900 p.p.s. The alternator consists of a ring-shaped frame carrying 60 inward-pointing magnetic poles. In the interior space a disc revolves having a laminated iron edge, slots in which carry a zigzag armature winding. The disc is driven by a 2·7-k.w. direct-current motor, either from batteries or supply circuits. The alternator can give a current of 30 amperes at 100 volts or so, and its normal speed is 1,800–2,000 revs. per minute, and frequency about 900-∿ to 1,000-∿.

The wave-form of the E.M.F. is, however, very far from being a simple sine curve. But this proves to be a great advantage, as it enables us to filter out three harmonics having frequencies in the ratio of 1 : 3 : 5, each of very pure sine-form. This was done as follows: A number of variable inductance coils were constructed, each consisting of a pair of pasteboard tubes, one of somewhat larger diameter than the other. On these were wound single layers of No. 14 S.W.G. cotton-covered copper wire, and the coils on the two tubes so connected by a piece of flexible wire that when the outer coil was slipped completely over the inner coil the inductance of the two in series was a maximum, but when drawn apart was reduced to a minimum. Three such inductances were constructed, the first being continuously variable between 1·38 and 2·37 millihenrys, the second between 0·683 and 1·163 millihenrys, and the third between 0·15 and 0·536 millihenrys. Also

for the second filter a coil was constructed capable of varying between 1·4 and 2·4 millihenrys. Associated with one or other of these variable inductances was a divided paraffin paper condenser of 20 microfarads capacity placed in series with the inductance, so that by appropriately adjusting the capacity C reckoned in microfarads to either 2, 4, or 20 microfarads and the inductance L of the coil reckoned in millihenrys to a suitable value, we could resonate the circuit to a frequency n, such that—

$$n = 5033/\sqrt{CL} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Assuming that the alternator is driven at a speed corresponding to a fundamental harmonic having a frequency of 920 p.p.s. we can filter out a harmonic of this frequency and also two others, one of frequency $3 \times 920 = 2,760$, and another of frequency $5 \times 920 = 4,600$, by placing across the terminals of the alternator one of the above inductances

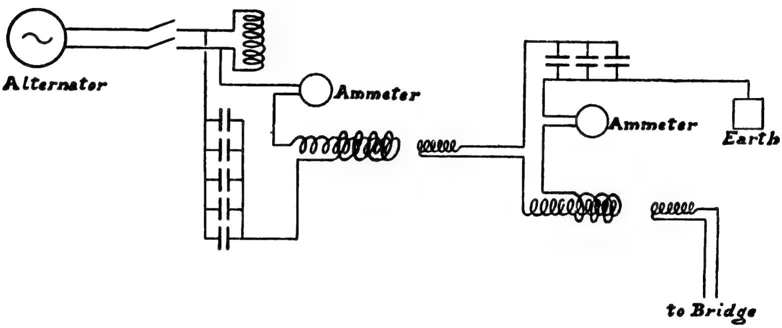


FIG. 4.—Scheme of Circuits for Filtering out the Harmonics from the Complex Wave-form of the Alternator E.M.F.

and a capacity tuned to the frequency to be selected. It was found necessary, however, to place a by-pass coil of a certain impedance and no capacity across the terminals of the alternator to provide a complete circuit in which the selected harmonic components can flow. Again, it was found that a single filtration is not sufficient to separate out a perfectly pure sine component. Hence a double filtration was employed. A pasteboard tube of smaller diameter than the inner of the two forming the sliding inductance was wound over with a suitable coil of insulated wire. This was slipped inside the primary sliding inductance and was joined in series with a suitable capacity varying from 0·25 to 8·25 microfarads to form a tuned secondary circuit. In this secondary circuit was inserted the primary circuit of an air-core transformer, and from the secondary circuit of this latter a pure sine curve electromotive force would be obtained of a frequency corresponding to the fundamental third or fifth harmonic according to the setting of the condensers and inductance coils. The complete filtration arrangement is as shown in the diagram in Fig. 4. The first

filter for the fundamental of 920 p.p.s. is obtained by using 20 microfarads capacity and 1·5 millihenry inductance, for the second harmonic of 2,760 p.p.s. by using 4 microfarads capacity and 0·81 millihenry inductance, and for the third of 4,600 p.p.s. by employing 2 microfarads capacity and 0·6 millihenry inductance. This method of filtering off the pure harmonics from an electromotive force curve of very irregular form is really more convenient than the possession of a single alternator of pure sine wave-form, as we are enabled thereby to obtain three well-separated frequencies from one single machine. No oscillograph except the Braun cathode ray oscillograph can be applied to inspect the wave-form, either original or filtered, when the frequency

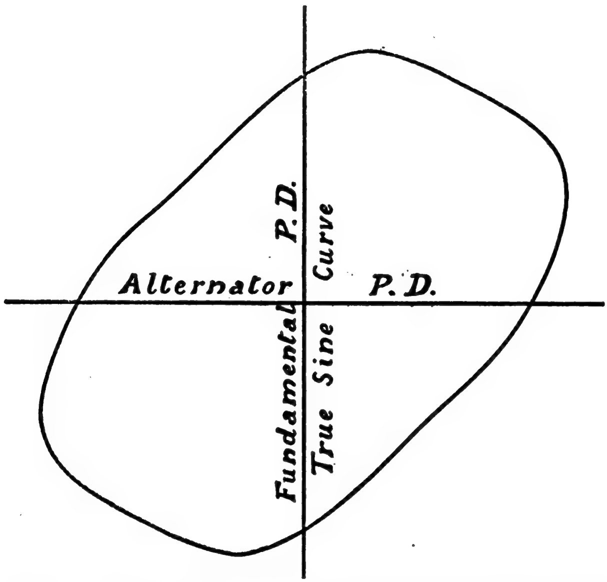


FIG. 5.—Reproduction of Cathode Ray Oscillogram of the High-frequency Alternator E.M.F. Curve.

lies between 900 and 5,000. We have, however, quite recently obtained a large Braun cathode ray tube and suitable electrostatic machine, which has enabled us to determine the wave-form of the E.M.F. curve of the alternator. The Braun tube contains a pair of deflecting plates in its interior, and these can be connected either to the terminals of the alternator or to the terminals of the condenser in the first harmonic filter, so that the cathode spot moves to and fro with a periodic motion. A pair of deflecting coils outside the tube carries the current through the above condenser, which is a nearly simple harmonic current. The amplitudes of these spot motions are adjusted so that they are equal and individually at right angles. Then the resultant motion of the

cathode spot in the case when the tube plates are connected to the condenser terminals is a circle showing that the wave-form of the harmonic is a sine curve. In the second case, it is an irregular closed curve (see Fig. 5), which can be seen on the phosphorescent screen and traced on paper by a camera lucida. This closed curve can be developed in wave-form and analysed by Fourier's theorem into its harmonics. In Fig. 6 the wave-form of the E.M.F. of the alternator is shown as a thick line, and the dotted lines show the analysis of the curve as far as the first, third, and fifth harmonics. These harmonics are picked out and intensified by our resonance circuits. Another method by which we can indirectly prove that the harmonics so selected have a simple sine-form is as follows:—

If an alternating electromotive force E, of frequency n, form factor

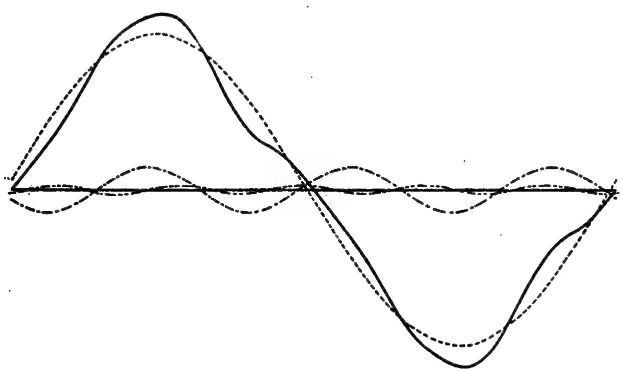


FIG. 6.—Wave Diagram and Harmonic Analysis of the High-frequency Alternator E.M.F.

The firm-line curve is the E.M.F. curve, and the dotted lines are the harmonics. The analysis is—

$$= 6{\cdot}15 \sin (pt + 3{\cdot}8^\circ) - 0{\cdot}90 \sin (3\,pt + 24{\cdot}1^\circ) + 0{\cdot}17 \sin (5\,pt - 52{\cdot}2^\circ).$$

f, and amplitude factor g, is applied to a non-dissipative condenser of capacity C, the current I flowing through it is given by the expression—

$$I = \frac{4f}{g} C n E \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

I and E being R.M.S. values. For a sine curve E.M.F. the factor $4f/g$ has a minimum value equal to 2π.

Hence if we apply an E.M.F. of frequency n to a condenser of capacity C, and measure the current I through it with a hot-wire ammeter and the voltage V at the terminals with an electrostatic voltmeter, and find that—

$$I/E = 2\pi n C,$$

this agreement gives an indication, though not an absolute proof, that the E.M.F. is of sine-form. The tests actually made consisted in

measuring the current I flowing into a condenser of known capacity and the potential difference V of its plates, and calculating the frequency n from the formula—

$$I = 2 \pi n C V,$$

and comparing this with the frequency of the fundamental or the harmonic as determined from the speed of the alternator. Thus, for instance, employing a standard mica condenser of capacity 0·498 microfarad, the application of the unfiltered electromotive force of the alternator gave a condenser current I = 0·0721 ampere, and a

TABLE I.

Capacity of Condenser tested = 0·498 microfarad = C.

Nature of Wave of E.M.F. used.	Current through Condenser in Amperes = I.	Potential Difference at Terminals of Condenser in Volts = V.	Frequency of E.M.F. used = n.	Calculated Value of the Factor $4f/g = I \times 10^6/n C V$.
Unfiltered E.M.F. of alternator ...	0·0721	9·90	868	16·85
Once filtered ... (First harmonic)	0·0435	15·80	840	6·55
Twice filtered ... (First harmonic)	0·0380	14·90	820	6·22
Once filtered ... (Third harmonic)	0·0810	10·00	2,574	6·29
Once filtered ... (Fifth harmonic)	0·0980	7·25	4,335	6·24
Theoretical sine curve	—	—	—	6·28

condenser terminal potential difference 9·9 volts. The calculated value of the frequency n by the formula—

$$n = I/2 \pi C V,$$

gave $n = 2{,}330$, whereas the actual frequency was 868. This shows that the unfiltered wave is very far from being a sine curve in form. If, however, the filtered-out fundamental electromotive force was employed, the current I was 0·0435 ampere, and the condenser potential difference was 15·8 volts. This gives $n = 880$ by calculation, and the actual frequency was 840. The above was for a single filtration. Employing a double filtration the agreement was still better. In this last case the condenser current was found to be 0·038 ampere, and the condenser potential difference to be 14·9 volts, and the calculated frequency was 816 whilst the observed was 820. We may exhibit the

results in another way by calculating for each case the value of the factor $4f/g$, and noting how far it differs from the theoretical value 2π for a sine wave-form.

It will be seen that the factor by which $n\,\mathrm{C}\,\mathrm{V}/10^6$ must be multiplied to give the condenser current closely approximates to 2π for the filtered harmonics, but is very different for the unfiltered wave of E.M.F. This therefore affords a strong indication, though not a complete proof, that the filtration, especially the double filtration, gives us an electromotive force closely approximating to a simple sine curve in form.

Having thus provided ourselves with a pure wave of E.M.F., we proceeded to consider the most useful method of determining the value of S/C.

It will be unnecessary to discuss the various methods which have been adopted for determining energy loss in dielectrics. As far as cables and condensers are concerned, the three chief methods are: (1) The wattmeter method, electrodynamic or electrostatic; (2) bridge methods; (3) angular measurement of the phase difference of the condenser current and potential difference, or of the complement of this angle.

The wattmeter method is applicable for the most part only when the losses are considerable or the voltage high. Moreover, it does not give us the separate values of S and C, but only their ratio. The measurement of very small phase angles, or those closely approaching 90°, presents some difficulties, but has been discussed by Dr. Sumpner and Dr. Drysdale.*

Hence, after considering all the possible methods, we gave preference to bridge methods, which would enable us to determine the conductivity and capacity separately, even when using very small condensers or short lengths of cable having a capacity of about a thousandth of a microfarad.

We may assume for the purpose of this measurement that every condenser can be represented as consisting of a perfect capacity C shunted by a conductance S, and hence that for simple periodic currents of frequency $n = p/2\pi$ the vector admittance of such a condenser is $\mathrm{S} + jp\mathrm{C}$, and its vector impedance is $(\mathrm{S} + jp\mathrm{C})^{-1}$ where $j = \sqrt{-1}$.

On the other hand, if a perfect condenser of capacity C is placed in series with an inductionless resistance R, then the vector impedance of the combination is $\left(\mathrm{R} - \frac{j}{\mathrm{C}p}\right)$ for simple periodic currents. Also the vector impedance of any inductive resistance coil without capacity is $\mathrm{R} + jp\mathrm{L}$. If the arms of a Wheatstone's bridge are filled in with

* C. V. Drysdale, "The Measurement of Phase Differences," *Electrician*, vol. 57, pp. 726 and 783, 1906, and vol. 58, pp. 160 and 199; and *Science Abstracts*, vol. 9, B, Nos. 1048 and 1410, 1906. W. E. Sumpner, "The Measurement of Small Differences of Phase," *Proceedings of the Physical Society*, vol. 19, p. 415, 1904; *Philosophical Magazine*, vol. 9, p. 155, 1905; and *Science Abstracts*, vol. 8, A, No. 1278, 1905.

any combination of inductances, capacities, or resistances, and if the bridge is supplied with a pure sinoidal electromotive force, and if a telephone is placed in the bridge circuit, then if J_1, J_2, J_3, J_4 are the vector impedances of the four arms, it is well known that the condition of perfect silence in the telephone is that these four impedances must be in simple proportion, so that $J_1/J_2 = J_3/J_4$, otherwise that $J_1 J_4 = J_2 J_3$, or the determinant—

$$\begin{vmatrix} J_1, & J_2 \\ J_3, & J_4 \end{vmatrix} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

By equating the so-called real and imaginary terms in this equation we are led to two separate equations, from which we can determine two of the quantities supposed unknown. The experimental measurement requires then two conditions to be fulfilled to obtain perfect

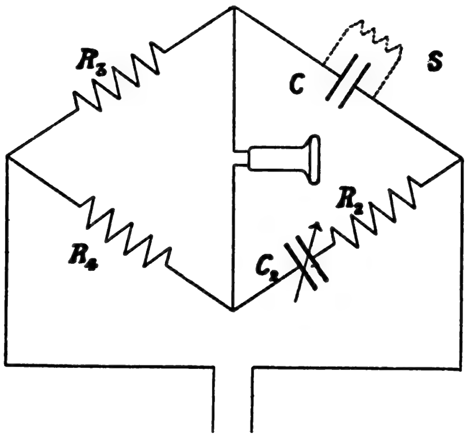


FIG. 7.—Wien Series Resistance Bridge.

silence in a telephone placed in the bridge. Amongst a number of alternating-current bridge methods given by Professor M. Wien* for the determination of capacities and inductances is one, now generally named the Wien resistance series method, which is as follows:—

A pair of condensers, C and C_2, one, viz., C having a shunt of conductance S in parallel with it, and the other, C_2, having a resistance R_2 in series with it, are arranged with two resistances R_3 and R_4 in a bridge as in Fig. 7. The resistance R_2, R_3, R_4 are adjusted until perfect silence is obtained in a telephone placed in the bridge circuit when the conjugate points are connected to a source of pure sine-form electromotive force.

* M. Wien, *Annalen der Physik*, vol. 44, p. 681, 1891. This method was used by B. Monasch for his work on "Energy Losses in Dielectrics." See *Science Abstracts*, vol. 10, A, No. 1084, 1907.

The condition of zero bridge current is then—

$$R_4/R_3 = (S + j p C)\left(R_2 - \frac{j}{p C_2}\right) \quad . \quad . \quad . \quad . \quad . \quad (29)$$

From which, by equating real and imaginary parts, we have—

$$S = p^2 C C_2 R_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

$$R_4/R_3 = S R_2 + C/C_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

The last two equations enable us to determine S and C separately. The assumption made, however, is that the resistances R_3 and R_4 are perfectly inductionless and without capacity. As it is not possible to

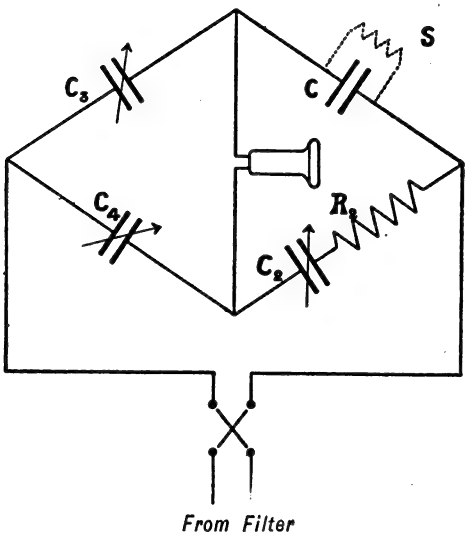


FIG. 8.—Fleming and Dyke Variable Capacity Bridge.

obtain absolutely inductionless resistances, it is better to substitute for the resistances R_3 and R_4 resistances of known but variable inductance. This last method was employed by F. W. Grover, Assistant Physicist in the Bureau of Standards, Washington, in a research entitled "Simultaneous Measurement of the Capacity and Power Factor of Condensers," published in 1907.* He replaced the resistances R_3, R_4 by two known variable inductances, and balanced the condenser of unknown absorption against another of no absorption or known absorption having in series with it an adjustable resistance. In considering the method best applicable for the purposes we had in view we were guided by the practical difficulties of obtaining very large and perfectly non-inductive resistances free from all capacity, since any unknown induct-

* F. W. Grover, *Bulletin of the Bureau of Standards*, vol. 3 p. 371, 1907.

ance or capacity in the resistances of the bridge arms may seriously vitiate the results.

Since it is an easier matter to obtain almost perfect non-dissipative condensers of variable capacity, we were finally led, after a good many preliminary experiments, to the following arrangement, constituting a capacity bridge having four capacities, viz., three variable known condensers and one capacity C to be determined in the four arms, one non-inductive resistance and the unknown condenser conductance S. The arrangement is as shown in Fig. 8, in which C_2, C_3, and C_4 are three air condensers of variable capacity, constructed of fixed semi-circular plates, and a movable set which can be rotated on a shaft carrying an index needle, so as to be included more or less between the fixed plates. These condensers were calibrated by the Carey-Foster method, and a curve constructed to convert scale readings to micro-microfarads or billionths of a farad. This curve is nearly a straight line.

The resistance R_2 is an inductionless, or practically inductionless, resistance, and C is the capacity of the condenser or cable operated upon, having a dielectric conductance represented by S.

The bridge is connected by one pair of terminals to the secondary circuit of the transformer in the second wave filter above described, by means of which it is supplied with a perfectly pure sine-form E.M.F., having a value of 4 or 5 volts. As we were concerned chiefly with telephonic frequencies, we did not consider it necessary to employ voltages on our condensers and cables much higher than usual telephonic voltages. The opposite corners of the bridge are connected to a sensitive high-resistance head telephone. The condenser or length of cable to be measured is then connected in as the fourth arm of the bridge. The experimental adjustment consists in varying the capacity of the condensers, C_3 and C_4, and the resistance R_2 for some selected value of the capacity C_2 until perfect silence is obtained on listening to the telephone. We then have four impedances which are in proportion, viz.:—

$$(S+jpC)^{-1}, \quad \left(R_2-\frac{j}{pC_2}\right), \quad -\frac{j}{pC_3}, \quad -\frac{j}{pC_4}.$$

Hence the bridge equation is—

$$\left(R_2-\frac{j}{pC_2}\right)(S+jpC)=C_3/C_4 \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

Equating real and imaginary parts we obtain the equations—

$$\frac{S}{Cp}=pC_2R_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

and—

$$\frac{C_3}{C_4}=\frac{C}{C_2}+R_2S \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

Having obtained the value of $S/Cp=x$ from equation (33), it is

most easy to calculate the separate values of S and C from the equations $C = \frac{C_2 C_3}{C_4} \times \frac{1}{1 + x^2}$, and hence $S = p\,C\,x$.

These equations give us S and C in terms of C_2, C_3, C_4, and R_2, and also S/Cp.

Experience showed us that certain precautions are necessary in employing this condenser bridge method. The separate condensers which form the arms of the bridge must not be too near together, as no mutual capacity must exist. Also connections must be made with fine wire, so that capacity in these is as far as possible avoided. The body of the observer must not approach too near the condensers when the actual balance of zero-point of sound is being obtained. The method of using two capacities in the ratio arms of the bridge has great advantages over that of using two resistances or inductances when measuring small condensers or short lengths of cable. Thus, for instance, if the condenser under test, denoted in the above formulæ by C, has a capacity of something of the order of 0·001 microfarad, and is operated at a frequency of, say, 1,000, then $1/Cp$ would be an impedance of the order of 150,000 ohms. Hence, if inductionless resistances are employed in the third and fourth bridge arms, these would have to be perfectly inductionless anti-capacity variable resistances of the order of 100,000 ohms or so, to obtain the conditions of maximum sensitivity for the bridge-arm ratios. Such large resistance boxes are not found in every laboratory or easily obtained. On the other hand, variable air condensers having a capacity of the order of zero to 0·002 microfarad capacity are a commercial article, and as they have practically no absorption they can be safely used as the ratio arms of the bridge. The practical adjustment then consists in varying the capacities of the two condensers C_3 and C_4, and the resistance R_2 for some selected value of the capacity C_2 until absolute silence is obtained in the telephone. The resistance R_2, which need never be very large, was an ordinary plug resistance box. But no difference was found when a special inductionless resistance made by Paul was employed. When using the range of frequencies we have employed, viz., 920 to 5,000 $\sim$, the use of a vibration galvanometer is out of the question. Hence the telephone employed by an observer with acute hearing is the only possible means of determining when the balance of the bridge is obtained. It may be pointed out incidentally that no accurate balance or well-defined zero can be obtained unless the electromotive force applied to the bridge has a very true sine waveform. Hence no arrangement such as a buzzer, hummer, or current interrupter of any kind can be substituted for the sine curve alternator or for the alternator and wave filter such as we have used.

It seems more easy to obtain a pure sine-form E.M.F. with the third and fifth harmonics than with the fundamental, and we have found it easier to obtain good readings with these higher frequencies than with the lower one.

Two other conditions are necessary to obtain consistent readings.

It is generally necessary to keep one point on the second filter circuit connected to earth. On referring to Fig. 4 it will be seen that one terminal of the condenser in the second filter circuit is connected to an earth-plate. Also it is necessary always to take two readings in every case with the connections between the corners of the bridge and the secondary circuit of the transformer in the second filter which supplies the bridge current interchanged. This is effected by the reversing switch inserted in the feeder circuit of the capacity bridge shown in Fig. 8. The two readings so taken are denoted by *d* and *r* in the following tabular results. The mean of these readings is taken.

The actual procedure in making a measurement is as follows: The condenser or cable under test having been joined into one arm of the bridge and the simple sinoidal E.M.F. applied, the capacities C_2, C_3, and C_4 are adjusted for some selected value of the resistance R_2 until silence is obtained in the telephone as nearly as possible, the capacities C_2, C_3, and C_4 being so chosen that they are nearly equal to C. A careful balance or complete silence is then obtained by the adjustment of R_2 and C_3 or C_4. The reversing switch is then thrown over and another balance obtained. The capacity C_2 is then altered by about 20 per cent., and a new adjustment made of C_3, C_4, and R_2 to obtain balance again, and a pair of readings taken with the connections reversed. Four readings are thus obtained and the mean of all taken. To secure good results the room must be very quiet, and no induction coils or high-frequency transformers at work very near or else disturbing sounds will be heard in the telephone.*

When, however, all the above-named precautions are taken the method appears to give very consistent results, which can be repeated, and agree amongst themselves. As a check we applied the method to test an air condenser made intentionally leaky by shunting it with a known resistance to ascertain whether the results given by it would enable us to separate out the true capacity and conductance of the combination. For this purpose an air condenser having a capacity of 430×10^{-12} farads or 0·00043 microfarad was shunted with a high resistance consisting of a wire megohm and a carbon megohm adjustable within certain limits. Three measurements were made:—

1. The carbon megohm ($= 1{\cdot}15 \times 10^6$ ohms) and the wire megohm ($= 1{\cdot}00 \times 10^6$ ohms) were joined in series and placed as a shunt to the condenser. Hence for this combination $C = 430 \times 10^{-12}$ farads and $S = (2{\cdot}15 \times 10^6)^{-1}$ mhos. The combination was tested by the above described bridge method at a frequency of 4,400 p.p.s., using the filtered fifth harmonic of the alternator. The balancing capacity and ratio capacities were found to be $C_2 = 476 \times 10^{-12}$ farads, $C_3 = 1{,}130 \times 10^{-12}$ farads, and $C_4 = 1{,}216 \times 10^{-12}$ farads, whilst the

* These observations are very trying, and put a considerable strain on the observer if prolonged. The actual experimental measurements recorded in this paper have been entirely conducted by Mr. G. B. Dyke, and for the most part have had to be carried out in the evening owing to the disturbances caused in the daytime by induction coils and transformers working in other parts of the College.

resistance R_2 was 2,975 ohms. We have then $p = 2\pi n = 27{,}600$, and hence from the bridge equations $C = 0{\cdot}000443$ microfarad, and $S = 0{\cdot}476 \times 10^{-6}$ mho or $1/S = 2{\cdot}10 \times 10^6$ ohms, or 2·1 megohms. The actual values were 2·15 megohms and 0·000430 microfarad.

2. The shunt was altered to consist of the carbon megohm and half of the wire megohm, being equal to 1·65 megohms. For the same frequency and value of R_2, as in the previous experiment, we found that the required capacities for balance were—

$$C_2 = 580 \times 10^{-12}, \quad C_3 = 409 \times 10^{-12}, \text{ and } C_4 = 540 \times 10^{-12}.$$

Hence by the formula we have $C = 0{\cdot}000439$ and $S = 0{\cdot}575 \times 10^{-6}$ mhos or $1/S = 1{\cdot}75$ megohm.

In another more carefully made measurement we shunted an air condenser, the capacity of which was found by the Carey-Foster method to be 0·001282 microfarad, with a carbon resistance of 1·46 megohm, for which, therefore, $S = 0{\cdot}69$ micromhos. Submitting the combination to the bridge test at three frequencies we obtained the following values :—

TABLE II.

Frequency n.	Conductance S Micromhos.	Capacity C Microfarads.	Calculated Ratio $\frac{S}{Cp}$
920	0·72	0·001287	0·096
2,760	0·73	0·001287	0·033
4,600	0·72	0·001287	0·019

Hence we obtain by this alternating-current bridge test almost exactly the true capacity for the air condenser as actually determined by the Carey-Foster method, and a close approximation to the true conductance of the shunt of known resistance which was used.

It will be seen from Table II. that the ratio S/Cp is inversely as the frequency. This is because the condenser is here shunted artificially with a resistance which is metallic in nature.

Accordingly it is clear that in these cases in which the true value of the capacity and conductance are known beforehand our method finds the correct values.

Having thus obtained confidence in the method, we prepared a number of small condensers having dielectrics respectively of dry Manilla paper, paraffined Manilla paper, celluloid (cinematograph film), gutta-percha, pure indiarubber, vulcanised indiarubber, ebonite, glass, mica, sulphur, thin slate, and other materials. The dielectrics were

sheets about 3·5 cm. by 12 cm. in size and 1 or 2 mm. or less in thickness, except the sulphur. The metal condenser plates were usually tinfoil, in the shape shown in Fig. 9 with a lug and with rounded corners and a sufficient number of sheets taken to give a capacity of the order of 0·001 of a microfarad or rather less.

In addition to the sheets of dielectric between the metal plates a considerable thickness of the same dielectric was added outside to carry the lines of force which proceed from the back sides of the outside metal plates. The complete condenser was bound up very tightly between two glass plates with silk tape. The condensers were of such size that they could easily be heated in a small electric oven, which forms a very convenient appliance for keeping such objects at a constant temperature. The condensers could also be sealed up in a glass tube when it was desired to expose them to a low temperature by immersing in melting ice or ice and salt or other cooling mixture.

They were tested as above described at three frequencies: viz., 920, 2,760, and 4,600 p.p.s., and at temperatures varying from $-15°$ C. to 80° C. At these frequencies and over this range of temperature we measured the alternating-current conductivity, the capacity, and the power factor of all the condensers. We also measured the same

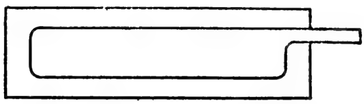


FIG. 9.—Condenser Plate and Sheet of Dielectric.

quantities for a dry-core paper-insulated telephone cable and for two samples of gutta-percha insulated cable. We also tested certain pure dielectrics such as paraffin wax and sulphur in the form of thicker flat plates. As the actual number of measurements on each condenser were very large, we have only given full details in the case of one dielectric, viz., glass, to show how the observations were tabulated, and we have given in other cases only the mean results of each set of measurements.

In the case of each condenser we measured as carefully as possible the total sectional area and thickness of the dielectric, and the ratio of these numbers or of area to thickness is given in each case so that the dielectric constant and the alternating resistivity can be approximately obtained from the measured capacity and conductance. This serves as a check on the accuracy of the measurements. For in a plate condenser, of which one plate has an area A sq. cm. and the dielectric a small thickness t and a dielectric constant k, the capacity in microfarads is approximately given by the formula—

$$C_{\text{mfds.}} = \frac{k\,A}{4\pi t} \cdot \frac{1}{9 \times 10^5} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

Hence we have—

$$k = \frac{36 \times 10^5 \times \pi}{\text{area/thickness}} \times C_{\text{mfds.}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

The value of k so determined cannot claim extreme accuracy, because in the above formula we have neglected the spreading of the lines of electric force near the edges of the metal plates, but nevertheless owing to the great differences in the dielectric constants of various specimens of the same substance it is not worth while to strain after very great accuracy, and it is sufficient to show whether our capacity measurements can be trusted. In all cases we have found that the dielectric constant we have obtained from our experiments falls within the limits of values obtained by other observers for dielectrics of the same name.

By dividing the observed conductance of the condensers by the dimension ratio for the dielectric, we have obtained approximate values for the specific conductivity of each substance for various frequencies and temperatures.

We are well aware that the determination of the specific resistance of dielectrics for *direct currents* by similar measurements made on plate condensers is liable to be affected by considerable errors if tinfoil or sheet metal electrodes are employed owing to want of perfect contact between the dielectric and the electrode.* On the other hand, it appears to us that this source of error is very much diminished or practically absent when alternating currents of high frequency are employed for the following reason: It has been shown in Part I. that if a condenser of capacity C is joined in series with a resistance R, the effective conductance of the combination for currents of frequency $n = p/2\pi$ is given by the expression $\frac{C^2 R^2 p^2}{1 + C^2 R^2 p^2} S$ where $S = 1/R$ is the conductance *per se* of the resistance. Hence if we have a sheet of dielectric and an electrode of tinfoil in which the contact is not absolutely perfect, this amounts to the connection in series of an air condenser and a high resistance. The above formula shows that for currents of high frequency and for dielectrics in which the quantity $C^2 R^2 p^2$ will be large compared with unity, the observed or apparent conductivity of the system so found will not be very different from the true conductivity of the dielectric for alternating currents of that frequency. To obtain convenient numbers for plotting we have expressed these specific conductivities in billionths of a mho ($= 10^{-12}$ mho) which for shortness we call a bi-mho. We can then obtain the specific conductivity of the dielectric *approximately* by multiplying the observed condenser conductance measured in micromhos by 10^6, and then dividing by the dimension ratio (area/thickness) for the dielectric

See R. Appleyard, "On Contact with Dielectrics," *Proceedings of the Physical Society*, vol. 19, p. 724, 1905; *Philosophical Magazine*, vol. 10, p. 485, 1905; and *Science Abstracts*, vol. 8, A, No. 2099, 1905, for information on the errors, introduced into specific resistance measurements of dielectrics by want of perfect contact of the electrodes when using direct currents.

used. The area is, of course, the total coated area on one side and the thickness is the mean thickness of all the sheets, we have then—

$$\rho = \left\{\begin{array}{l}\text{resistivity in megohms}\\ \text{per centimetre cube}\\ \text{of the dielectric}\end{array}\right\} = \frac{\text{area/thickness}}{\text{S (in micromhos)}} \quad . \quad . \quad . \quad (37)$$

$$\sigma = \left\{\begin{array}{l}\text{specific conductivity in}\\ \text{bi-mhos per centi-}\\ \text{metre cube of the}\\ \text{dielectric}\end{array}\right\} = \frac{10^6 \times \text{S (in micromhos)}}{\text{area/thickness}} \quad . \quad (38)$$

Hence the value of σ and k can be found from the capacity and conductance measurements taken at various temperatures and frequencies.

TABLE III.

Dielectric: Crown glass (microscope slide).
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0206 cm.

$$\text{Dimension ratio} = \frac{\text{area}}{\text{thickness}} = 2{,}670.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductivity in Bi-mhos per Centimetre Cube σ.
920	0	0·102	0·001523	0·012	0·012	38
	17	0·158	0·001554	0·018	0·018	59
	49	0·311	0·001610	0·034	0·034	116
	62	0·631	0·001692	0·064	0·064	236
	89	1·515	0·001873	0·140	0·138	567
2,760	0	0·258	0·001509	0·010	0·010	96
	17	0·417	0·001543	0·016	0·016	156
	49	0·709	0·001584	0·026	0·026	265
	61	1·305	0·001646	0·046	0·046	488
	88	2·715	0·001761	0·089	0·089	1,016
4,600	0	0·423	0·001508	0·010	0·010	158
	17	0·657	0·001538	0·015	0·015	246
	47	0·999	0·001581	0·022	0·022	374
	62	1·867	0·001637	0·040	0·040	700
	87	3·545	0·001720	0·071	0·071	1,327

Also the rate of energy dissipation in any condenser or cable made with these dielectrics can be pre-determined. For this rate is proportional to the product of the total conductance and the mean-square value of the potential difference. Thus if a plate condenser has an

area of one plate equal to A, and a thickness of dielectric t, and a potential difference V between its plates, then the total power in watts dissipated in it is $\frac{V^2 A}{\rho t}$, and can thus be determined by the aid of the value of ρ calculated from our tables for the different dielectrics tested and for the temperature and frequency range stated. We proceed then to describe the measurements made with each sample of dielectric.

I. Glass.

The material we selected for tests was thin crown glass of the kind used for the covers of microscopic slides. This was cut for us into small sheets 12 × 3·5 cm. and built up into a condenser with interposed sheets of tinfoil. The total coated surface of dielectric on each side was 55 sq. cm. and the thickness of dielectric 0·0206 cm. Hence the ratio of area/thickness for the dielectric is 2,670.

This condenser had a capacity of about 1,400 electrostatic units, and it was tested on the capacity bridge as above described at three frequencies—920, 2,760, and 4,600 p.p.s.—and at five temperatures—viz., 0° C., 17° C., 49° C., 62° C., and 89° C.

The compressed results are given in Table III. The first and second columns give the frequency ($n = p/2\pi$) and temperature, the third the conductance (S) in micromhos. The reciprocal of this last number is the dielectric resistance in megohms. The fourth column gives the capacity (C) in microfarads, and the fifth the value of S/Cp, the sixth the power factor of the condenser, and the seventh the conductivity of the dielectric in bi-mhos per centimetre cube.

To show how these results are obtained we give in Table IV. the full details of the experimental numbers which will be intelligible in the light of the previous explanations. The capacities are, however, stated in micro-microfarads to economise space in this Table IV. The general correctness of the capacity values can be checked by noticing that if we take the value of any measured capacity, say, 0·001554 microfarad at 17° C. and 920 p.p.s., and determine by the formula (36) the value of the dielectric constant we obtain $k = 6{\cdot}57$, which is known to be the approximate value of the dielectric constant for crown glass. By the aid of formula (37) we can obtain also the alternating-current resistivity of the glass for any frequency and temperature within the range employed.

Thus at 17° C. and 920 p.p.s. it is 2,670/0·158 = 16,900 megohms per centimetre cube. Hence we can obtain the power taken up in any condenser made of this glass corresponding to any given potential difference of the plates, provided we assume, as we may fairly do, that the energy loss varies as the square of the potential difference. Thus, suppose we require the power absorbed by a glass condenser having 1,000 sq. cm. of coated surface and 3 mm. thickness. When the R.M.S. value of the applied potential difference is 1,000 volts and the

TABLE IV.

Detailed Experimental Results for Glass.

Temperature T, °C.	Frequency, *n*.	Method of Connection.	Resistance Ohms. R_2	Capacities in Microfarads × 10^6. $C_2 \times 10^6$.	$C_3 \times 10^6$.	$C_4 \times 10^6$.	$C \times 10^6$.	Conductance Micromhos. S	$\frac{S}{Cp}$
0	920	*d*	1,520	1,282	1,216	1,021	1,526	0·100	0·0113
		r	1,570	1,282	1,216	1,024	1,521	0·102	0·0116
		r	2,100	1,041	1,216	832	1,522	0·111	0·0126
		d	1,800	1,041	1,216	832	1,522	0·095	0·0108
						Mean	1,523	0·102	0·0116
0	2,760	*d*	530	1,041	1,216	840	1,509	0·251	0·0096
		r	560	1,041	1,216	840	1,509	0·264	0·0101
		r	460	1,282	1,216	1,032	1,509	0·267	0·0102
		d	430	1,282	1,216	1,032	1,509	0·251	0·0096
						Mean	1,509	0·258	0·0099
0	4,600	*d*	250	1,282	1,216	1,034	1,507	0·405	0·0093
		r	270	1,282	1,216	1,031	1,510	0·436	0·0100
		r	340	1,041	1,216	840	1,509	0·444	0·0102
		d	310	1,041	1,216	841	1,507	0·405	0·0093
						Mean	1,508	0·423	0·0097
17	920	*d*	2,100	1,282	1,216	1,000	1,560	0·141	0·0156
		r	2,600	1,282	1,216	1,000	1,560	0·174	0·0193
		r	3,200	1,041	1,216	818	1,549	0·172	0·0193
		d	2,700	1,041	1,216	819	1,547	0·146	0·0163
						Mean	1,554	0·158	0·0176
17	2,760	*d*	890	1,041	1,216	829	1,530	0·421	0·0159
		r	870	1,041	1,216	820	1,547	0·415	0·0155
		r	670	1,282	1,216	1,007	1,550	0·400	0·0149
		d	730	1,282	1,216	1,010	1,543	0·432	0·0162
						Mean	1,543	0·417	0·0156
17	4,600	*d*	480	1,041	1,216	830	1,528	0·635	0·0144
		r	480	1,041	1,216	821	1,542	0·641	0·0144
		r	410	1,282	1,216	1,010	1,546	0·678	0·0152
		d	410	1,282	1,216	1,017	1,536	0·674	0·0152
						Mean	1,538	0·657	0·0148

The letters *d* and *r* in the third column of Table IV. denote that the corresponding readings were taken with the connections of bridge and filter circuit direct connected (*d*) or reversed (*r*) by the key. In the compressed tables of results the mean of these four readings opposite each frequency is taken.

TABLE IV—(*continued*).

Detailed Experimental Results for Glass—(*continued*).

Temperature T, °C.	Frequency, n.	Method of Connection.	Resistance Ohms. R_2	Capacities in Microfarads × 10^6. $C_2 \times 10^6$.	$C_3 \times 10^6$.	$C_4 \times 10^6$.	$C \times 10^6$.	Conductance Micromhos S	$\frac{S}{Cp}$
49	920	*d*	4,300	1,282	1,216	970	1,607	0·296	0·0319
		r	4,600	1,282	1,216	968	1,610	0·317	0·0341
		r	5,900	1,041	1,216	785	1,611	0·332	0·0356
		d	5,300	1,041	1,216	785	1,611	0·297	0·0319
						Mean	1,610	0·311	0·0344
48	2,760	*d*	1,400	1,041	1,216	803	1,578	0·690	0·0252
		r	1,470	1,041	1,216	800	1,582	0·726	0·0265
		r	1,170	1,282	1,216	982	1,589	0·715	0·0260
		d	1,150	1,282	1,216	983	1,587	0·704	0·0256
						Mean	1,584	0·709	0·0258
47	4,600	*d*	620	1,282	1,216	990	1,574	1·040	0·0229
		r	560	1,282	1,216	984	1,584	0·946	0·0207
		r	690	1,041	1,216	799	1,584	0·951	0·0208
		d	770	1,041	1,216	800	1,582	1·060	0·0232
						Mean	1,581	0·999	0·0219
62	920	*d*	8,370	1,282	1,216	915	1,697	0·606	0·0620
		r	9,000	1,282	1,216	912	1,703	0·656	0·0667
		r	11,200	1,041	1,216	743	1,697	0·661	0·0675
		d	10,200	1,041	1,216	745	1,691	0·600	0·0614
						Mean	1,692	0·631	0·0644
61	2,760	*d*	2,520	1,041	1,216	770	1,642	1·293	0·0455
		r	2,570	1,041	1,216	767	1,649	1·322	0·0464
		r	2,090	1,282	1,216	945	1,648	1·321	0·0464
		d	2,030	1,282	1,216	947	1,643	1·283	0·0451
						Mean	1,646	1·305	0·0459
62	4,600	*d*	1,100	1,282	1,216	956	1,638	1·920	0·0407
		r	1,030	1,282	1,216	950	1,639	1·803	0·0382
		r	1,280	1,041	1,216	770	1,646	1·829	0·0385
		d	1,360	1,041	1,216	779	1,624	1·917	0·0409
						Mean	1,637	1·867	0·0396

The letters *d* and *r* in the third column of Table IV. denote that the corresponding readings were taken with the connections of bridge and filter circuit direct connected (*d*) or reversed (*r*) by the key. In the compressed tables of results the mean of these four readings opposite each frequency is taken.

TABLE IV—(*continued*).

Detailed Experimental Results for Glass—(continued).

Temperature T, °C.	Frequency. n.	Method of Connection.	Resistance Ohms. R_2	Capacities in Microfarads × 10^6.				Conductance Micromhos. S	$\frac{S}{Cp}$
				$C_2 \times 10^6$.	$C_3 \times 10^6$.	$C_4 \times 10^6$.	$C \times 10^6$.		
89	920	*d*	18,640	1,282	1,216	816	1,877	1·493	0·138
		r	19,120	1,282	1,216	815	1,875	1·538	0·142
		r	23,800	1,041	1,216	665	1,869	1·541	0·143
		d	22,900	1,041	1,216	666	1,869	1·488	0·138
						Mean	1,873	1·515	0·140
88	2,760	*d*	4,930	1,041	1,216	714	1,761	2·718	0·0890
		r	4,980	1,041	1,216	714	1,761	2·741	0·0899
		r	4,000	1,282	1,216	878	1,762	2·718	0·0889
		d	3,960	1,282	1,216	879	1,760	2·681	0·0880
						Mean	1,761	2·715	0·0890
87	4,600	*d*	1,930	1,282	1,216	903	1,718	3·546	0·0715
		r	1,880	1,282	1,216	900	1,723	3·462	0·0696
		r	2,420	1,041	1,216	733	1,720	3·620	0·0729
		d	2,380	1,041	1,216	735	1,717	3·550	0·0716
						Mean	1,720	3·545	0·0714

The letters *d* and *r* in the third column of Table IV. denote that the corresponding readings were taken with the connections of bridge and filter circuit direct connected (*d*) or reversed (*r*) by the key. In the compressed tables of results the mean of these four readings opposite each frequency is taken.

frequency 920 and temperature 17° C., the total resistance of the glass to such alternating currents would be—

$$(16{,}900 \times 0{\cdot}3)/1{,}000 = 5 \text{ megohms},$$

and the power absorption in watts would therefore be 0·2 watt for this R.M.S. value of the potential difference.

In the next place, we notice that as temperature increases the alternating-current conductance rapidly increases, but the rate of increase with temperature is different for each frequency. With 920 p.p.s. it is 15 times greater at 89° C. than it is at 0° C., but for 4,600 p.p.s. it is only about 9 times greater at 89° C. than at 0° C.

Again, the capacity increases with temperature, but, for the same temperature, decreases as frequency increases. If k_t is the dielectric constant at t° and k_0 is the value at 0° C., then $k_t = k_0 (1 + a\,t)$ for any particular frequency.

At a frequency at 920 p.p.s. the temperature coefficient (a) of the capacity or of the dielectric constant is equal to 0·0026 nearly over the

range of temperature 0° C. to 100° C. It is 0·0019 nearly for the same range at 2,760 p.p.s., and 0·0016 for 4,600 p.p.s. Hence the coefficient itself diminishes as frequency increases.

If we plot out the values of S/Cp in terms of temperature, as in Fig. 10, we obtain three curves which run together up to about 40° C. and then diverge considerably. These curves show the variation of S/Cp with frequency and temperature. It is seen that up to about 40° C. S/Cp is nearly independent of frequency, but that beyond that point the value of S/Cp decreases as frequency increases. This clearly points to the fact that the dielectric conductance is a function of the frequency of the form $S = A + Bn$, where A and B are coefficients which vary with the temperature. The quantity A is small below 17° C., but rapidly increases with temperature. It is well known that at temperatures

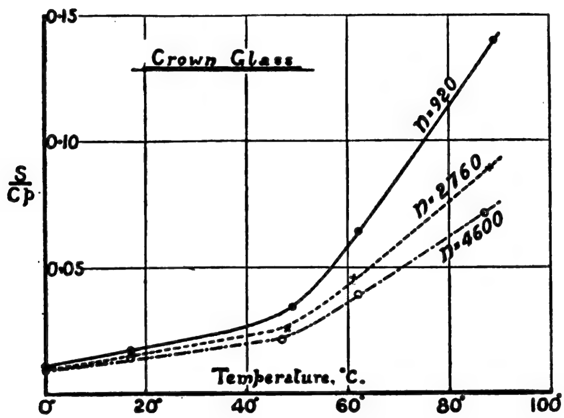


FIG. 10.—Variation of $\frac{S}{Cp}$ (Power Factor) with Temperature and Frequency for Glass Condenser.

much above the normal glass is an electrolyte. Hence it is highly probable that the coefficient A represents that part of the conductance which is electrolytic in nature. A simple calculation shows that within the range of the frequency n employed by us we can express the observed values of S in micromhos at the different temperatures approximately as follows :—

At 0° C.	... ...	$S = 0{\cdot}023 + 0{\cdot}000087\,n$ micromhos.
„ 17° C.	... ...	$S = 0{\cdot}023 + 0{\cdot}00014\,n$ „
„ 49° C.	... ...	$S = 0{\cdot}136 + 0{\cdot}00019\,n$ „
„ 62° C.	... ...	$S = 0{\cdot}320 + 0{\cdot}00034\,n$ „
„ 88° C.	... ...	$S = 1{\cdot}000 + 0{\cdot}00057\,n$ „

It is clear that both the coefficients A and B increase rapidly with the temperature.

If the expressions for S above given are multiplied by 10^6, and then divided by the ratio of cross-sectional area to thickness for the dielectric, which in this case is 2,670, we shall obtain expressions in the form $a + b\,n$ for the conductivity (σ) per centimetre cube in bi-mhos.

Thus for glass at 17° we have—

$$\sigma = 8{\cdot}61 + 0{\cdot}0524\,n \text{ (in bi-mhos)},$$

where n is the frequency.

The reciprocal of σ is the resistivity per centimetre cube in mega-megohms. The values of σ in terms of frequency and temperature are plotted in Fig. 11.

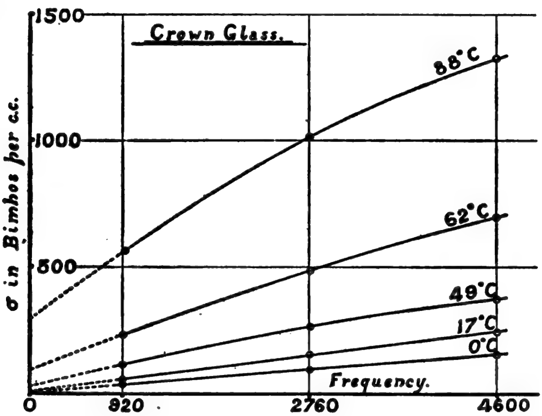


FIG. 11.—Variation of Conductivity with Temperature and Frequency for Glass Condenser.

The lines representing the variation of conductivity with frequency are in most cases nearly straight lines, thus showing that σ is a function of n of the form $\sigma = a + b\,n$.

The quantity a corresponds probably to the direct-current conductivity. Both a and b increase rapidly with rise of temperature. The temperature at which the lines begin to have a sensible intercept on the conductivity axis for $n = 0$ corresponds to the temperature at which the three lines in Fig. 10 begin to separate and turn upwards. This temperature is possibly that at which electrolytic conduction in the glass may commence. The curves show clearly that there are two kinds of conductivity which may be called provisionally the A and B conductivities, both of which increase with temperature, and one of which (the B conductivity) is nearly proportional to the frequency. The A conductivity is possibly electrolytic in nature. The total alternating conductivity is determined by the two together. At high temperature glass has very considerable electrolytic conductivity.

II. Celluloid.

A condenser was made up with thin transparent celluloid sheet as used for photographic films. The total exposed area was 55 sq. cm., and the thickness of dielectric was 0·0376 cm., and ratio of area to thickness was 1,468. The electrodes were thin copper foil in this case. This condenser was tested on the capacity bridge, and an epitome of the result is given in Table V. for various frequencies

Table V.

Dielectric: Celluloid. *Electrodes:* Copper foil.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0376 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}468.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarad C.	$\frac{S}{Cp}$	Power Factor	Conductivity in Bi-mhos per Centimetre Cube σ.
920	0	0·028	0·000595	0·008	0·008	19
	19	0·099	0·000666	0·026	0·026	67
	42	0·414	0·000727	0·099	0·099	281
	60	1·270	0·000808	0·273	0·263	863
	81	5·110	0·000971	0·912	0·674	3,490
2,760	0	0·083	0·000592	0·008	0·008	57
	19	0·226	0·000659	0·020	0·020	154
	45	0·706	0·000705	0·058	0·058	482
	60	1·810	0·000764	0·137	0·136	1,234
	80	5·850	0·000850	0·397	0·369	3,990
4,600	0	0·148	0·000590	0·009	0·009	101
	19	0·344	0·000657	0·018	0·018	235
	47	0·934	0·000696	0·047	0·047	628
	60	2·250	0·000749	0·104	0·104	1,535
	81	6·400	0·000824	0·279	0·269	4,370

and temperatures. It will be seen that the capacity at ordinary temperatures is nearly independent of the frequency, but at higher temperatures it decreases slightly as frequency rises.

It will be noticed how rapidly the power factor and conductivity increase with temperature.

At 81° C. and 920 p.p.s. the current in this celluloid condenser is only 47° 36′ ($=\cos^{-1} 0{\cdot}674$) in advance of the terminal potential difference instead of being 90° as in a perfect condenser.

The dielectric conductance S in micromhos can be expressed by

a formula of the type $S = A + Bn$, where n is the frequency and A and B are coefficients which increase rapidly with the temperature.

The approximate values of A and B for the various temperatures are as follows:—

At 0° C.	$S = 0 + 0{\cdot}00003\,n$
„ 19° C.	$S = 0{\cdot}038 + 0{\cdot}000066\,n$
„ 42° C.	$S = 0{\cdot}285 + 0{\cdot}00014\,n$
„ 60° C.	$S = 1{\cdot}000 + 0{\cdot}00027\,n$
„ 80° C.	$S = 4{\cdot}78 + 0{\cdot}00036\,n$

Hence the A and B terms increase with temperature, the A term very

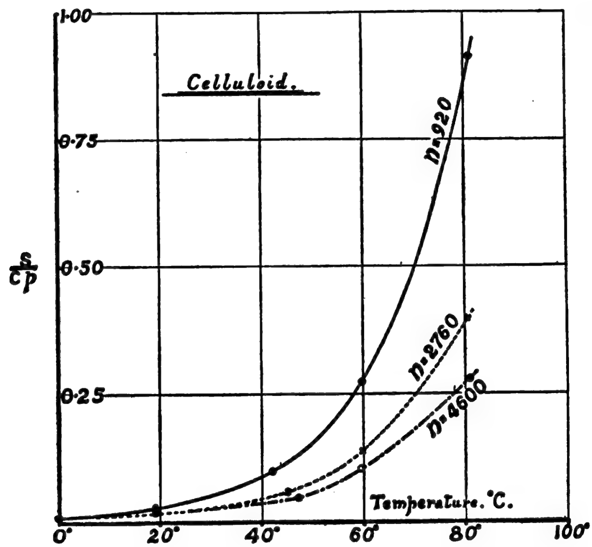


FIG. 12.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for Celluloid Condenser with Copper Foil Electrodes.

quickly indeed. Accordingly above 0° C. the value of S/Cp is not independent of frequency, but varies, as shown by the curves in Fig. 12, very rapidly with the temperature and frequency. It varies more rapidly with lower frequencies and for the same temperature decreases with rise of frequency. The dielectric constant (k_t) at any temperature t can be expressed in terms of the dielectric constant (k_0) at 0° C. by the formula—

$$k_t = k_0\,(1 + a\,t)$$

where the temperature coefficient a has the value 0·0078 for this condenser for a frequency of 920 p.p.s., 0·0054 for a frequency 2,760,

and 0·0049 for a frequency 4,600, being thus about three times that of glass.

As in the case of glass, we can obtain a number of nearly linear expressions in the form $\sigma = a + b\,n$ for the conductivity at various frequencies and temperatures. These are set out as lines in Fig. 13.

The extremely rapid increase in the value of the power factor S/Cp with temperature and its 920 p.p.s. and also the abnormally large value of the conductivity σ at 80° C. for this celluloid condenser made up with copper foil electrodes excited our suspicions, and we therefore examined the dielectric after it had been heated for some time to 80° C. We found that the celluloid had become deeply discoloured in such fashion as to suggest that the copper foil electrodes had acted chemically upon it at high temperatures. Accordingly another condenser

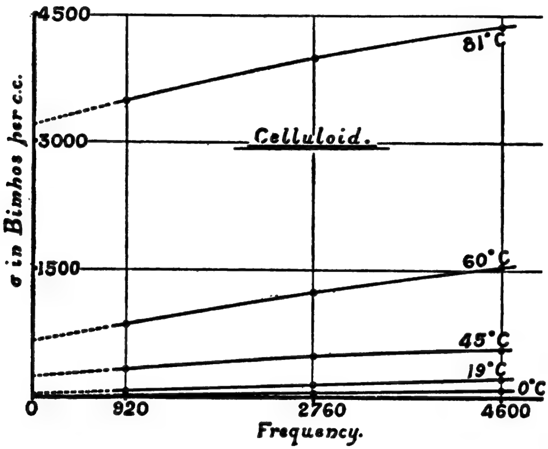


FIG. 13.—Variation of Conductivity with Temperature and Frequency for Celluloid Condenser with Copper Foil Electrodes.

was made up with rather thinner transparent celluloid sheet and tinfoil electrodes, and carefully tested for us on the capacity bridge by Mr. G. E. Bairsto. The result are embodied in Table VI. and graphically depicted in Figs. 14 and 15.

A subsequent examination of the celluloid condenser made up with tinfoil electrodes showed that there was no visible indication of any action of the tin on the celluloid, and the low temperature readings were found to repeat again accurately after heating to 80° C. Hence the observations in Table V. are clearly vitiated, and those in Table VI. must be taken as giving the true values for the celluloid dielectric. The necessity for care to avoid using electrodes which may have a chemical action on the dielectric at any temperature used is thus clearly indicated. From the figures given in Table VI. and applying formula (36) we find that the dielectric constant of celluloid at 15° C. and for 920 p.p.s. is

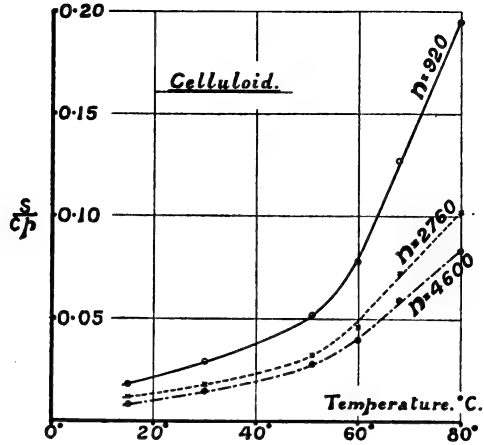


FIG. 14.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for Celluloid Condenser with Tinfoil Electrodes.

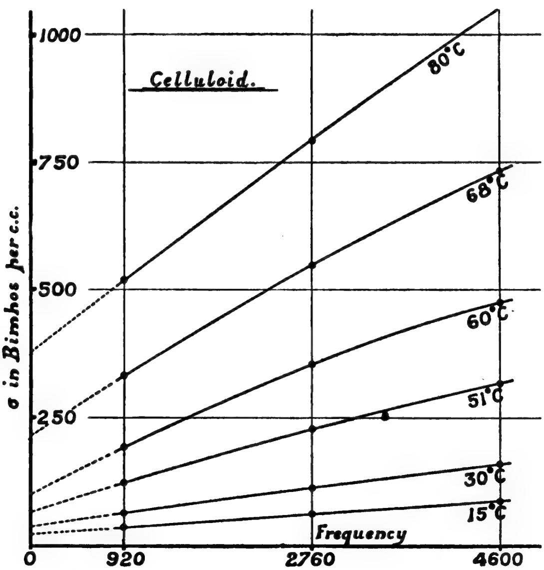


FIG. 15.—Variation of Conductivity with Temperature and Frequency for Celluloid Condenser with Tinfoil Electrodes.

very near 4·0, and that the temperature coefficient of the dielectric constant is positive and equal to 0·005 for 920 p.p.s. between 15° C. and 80° C., and is 0·0043 for 2,760 p.p.s. and 0·004 for 4,600 p.p.s.

The action of the copper electrodes was found to augment both the dielectric constant and its temperature coefficient, but we consider that for alternating currents of about 1,000 p.p.s. the value of the dielectric constant k_t for this transparent celluloid at any temperature t° C.

TABLE VI.

Dielectric : Celluloid. *Electrodes :* Tinfoil.
Approximate Dimensions : Area = 57 sq. cm.
Thickness = 0·0146 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 3{,}900.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductivity in Bi-mhos per Centimetre Cube σ.
920	15	0·092	0·001385	0·0115	0·0115	23·7
	30	0·199	0·001505	0·0229	0·0229	51·0
	51	0·481	0·001623	0·0520	0·0520	124·0
	60	0·745	0·001675	0·0780	0·0780	192·0
	68	1·290	0·001772	0·1270	0·1260	332·0
	80	2·020	0·001820	0·1950	0·1910	518·0
2,760	15	0·246	0·001375	0·0115	0·0115	63·0
	30	0·436	0·001465	0·0180	0·0180	112·0
	51	0·895	0·001605	0·0323	0·0323	228·0
	60	1·380	0·001640	0·0460	0·0460	355·0
	68	2·130	0·001702	0·0724	0·0723	548·0
	80	3·080	0·001745	0·1020	0·1020	792·0
4,600	15	0·499	0·001375	0·0117	0·0117	124·0
	30	0·621	0·001454	0·0147	0·0147	160·0
	51	1·250	0·001570	0·0277	0·0277	316·0
	60	2·800	0·001620	0·0399	0·0398	475·0
	68	2·850	0·001680	0·0589	0·0588	732·0
	80	4·120	0·001700	0·0834	0·0831	1,055·0

between 0° C. and 100° C. derived from values in Table VI., is approximately given by the formula—

$$k_t = 4·0\ (1 + 0·005\ t),$$

provided that electrodes are used which do not act chemically upon celluloid. If we take the values for the conductivity from Table VI. and plot them in terms of frequency we find that they plot into nearly

straight lines as in Fig. 15. Hence we can approximately express σ for celluloid at various temperatures and frequencies n as follows:—

$$\begin{aligned}\text{At } 15^\circ \text{ C. } \sigma &= 3 + 0{\cdot}022\, n\\ ,,\ 30^\circ \text{ C. } \sigma &= 40 + 0{\cdot}025\, n\\ ,,\ 60^\circ \text{ C. } \sigma &= 122 + 0{\cdot}077\, n\\ ,,\ 80^\circ \text{ C. } \sigma &= 384 + 0{\cdot}146\, n\end{aligned}$$

Therefore $\sigma = a + b\,n$, where a and b are functions of the temperature and increase very quickly with it. If we put $n = 0$ we have $\sigma = a$, and this should give us the value of the direct-current conductivity, which at 15° C. should be 3 bi-mhos per centimetre cube.

Mr. Bairsto has measured carefully, using mercury electrodes, the direct-current conductivity of this same sheet celluloid, and finds at 15° C. a direct-current conductivity of about 1 bi-mho per centimetre cube.

From the figures in Table VI. it will be seen that the power factor of celluloid increases rapidly with temperature at any one frequency, but decreases with frequency at any one temperature, and for low frequencies and rising temperatures approximates to unity. In fact, near 100° C. and even for a frequency as high as 900 p.p.s. it becomes nearly unity. This is entirely in accordance with the observations of Signor G. Vallauri, who found for a certain celluloid condenser power factors near 0·9 at ordinary temperatures for frequencies of 20 to 40 p.p.s.* Celluloid becomes chemically very unstable and even explosive at temperatures rather above 120° C., and at quite low temperatures exhibits in a marked manner the phenomena of "absorption."

Our values for its alternating-current conductivity receive some degree of confirmation from measurements made with direct currents by Mr. Addenbrooke. He states in a recent article † that he measured carefully the direct-current resistivity of a sheet of transparent celluloid, using mercury electrodes to eliminate contact resistance, and found it to be 40,000 megohms per centimetre cube, presumably at ordinary temperatures. Now this is equivalent to a conductivity of 25 bi-mhos per centimetre cube.

The value we have given above for the alternating conductivity of our transparent celluloid at 15° C. is 3 bi-mhos per centimetre cube. If our specimen of celluloid had not been subjected to previous heating to 80° C. it would have given much larger values for σ at 15° C., and hence the intercept a would have been greater than 3 and more in agreement with Mr. Addenbrooke's value, assuming that his was not previously heated.

III. Paper.

Some preliminary experiments made with Manilla paper and with ordinary white blotting-paper as a dielectric proved without doubt that

* G. Vallauri, "Some Investigations on a Celluloid Condenser," *Electrician*, vol. 66, p. 18, 1910; *Atti della Associazione Elettrotecnica Italiana*, vol. 14, p. 227, 1910; and *Science Abstracts*, vol. 13, B, Nos. 737 and 750, 1910.

† G. L. Addenbrooke, on "The Electrical Properties of Celluloid," *Electrician*, vol. 66, p. 629, 1911.

in the case of fibrous and moisture-absorbing dielectrics, the presence of water exercises the greatest effect upon the value of the ratio S/Cp and therefore upon the power factor of condensers made with them. We found that very considerable desiccation was necessary to free such substances as paper from all moisture and obtain the true values of the alternating-current capacity and conductance. As an

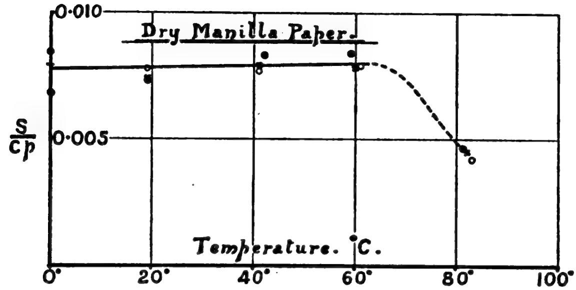


FIG. 16.—Values of $\frac{S}{Cp}$ for various Temperatures and Frequencies for Manilla Paper Condenser.

Note.—Observations at 920 p.p.s. represented by black dots; ditto at 2,760 by crosses and at 4,600 by small circles.

instance of the effect of this, we studied the dielectric properties of Manilla paper, a tough brownish paper much used for cable insulation.

A condenser was made up of sheets 12 × 3·5 cm. of this paper after very carefully drying it in an electric oven. The capacity and conductance were then measured on our bridge at the usual three fre-

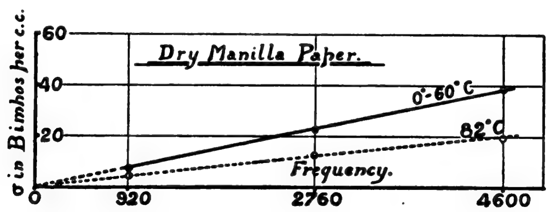


FIG. 17.—Variation of Conductivity with Temperature and Frequency for Manilla Paper.

quencies and five temperatures. An epitome of the results is given in Table VII. and the plotting of S/Cp in terms of temperature and frequency shown in Fig. 16. It will be seen that from 0° C. to beyond 60° C. the value of S/Cp is quite constant and independent of frequency or temperature. The capacity rises very slowly with temperature and decreases very slightly with increase of frequency. The conductivity

increases slightly with temperature up to 60° C., but there is then a sudden decrease, which we attribute to still more complete drying out of all moisture when the paper is kept some time at 80° C.

It will be seen from the Table VII. that the alternating-current conductivity rises as usual with frequency and temperature, and within the limits of frequency we have used it can be expressed by a formula

TABLE VII.

Dielectric: Manilla paper, after careful drying.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0157 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 3{,}500.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductivity in Bi-mhos per Centimetre Cube σ.
920	0	0·022	0·000570	0·007	0·007	6
	19	0·025	0·000603	0·007	0·007	7
	42	0·029	0·000606	0·008	0·008	8
	59	0·029	0·000607	0·008	0·008	8
	80	0·015	0·000580	0·005	0·005	4
2,760	0	0·078	0·000568	0·008	0·008	22
	19	0·075	0·000601	0·007	0·007	21
	41	0·079	0·000603	0·008	0·008	23
	60	0·082	0·000604	0·008	0·008	23
	82	0·045	0·000576	0·005	0·005	13
4,600	0	0·137	0·000568	0·008	0·008	39
	19	0·135	0·000601	0·008	0·008	39
	41	0·134	0·000601	0·008	0·008	38
	61	0·139	0·000607	0·008	0·008	39
	83	0·069	0·000575	0·004	0·004	20

of the type $S = A + Bn$ for various frequencies as follows: For all temperatures from 0° C. to 60° C. we have approximately—

$$S = 0{\cdot}000027\,n,$$

where n is the frequency, thus showing that the coefficient A is zero. The specific conductivity curve as shown in Fig. 17 is a straight line passing through the origin.

The resistivity ρ at 19° C. and 920 p.p.s. obtained by formula (36) is $\rho = 3{,}500/0{\cdot}025 = 140{,}000$ megohms per centimetre cube.

The dielectric constant k of this Manilla paper obtained from

the measured capacity and dimension ratio at 19° C. and 920 p.p.s. is—

$$k = \frac{11 \cdot 3}{3{,}500} \times 603 = 1 \cdot 95.$$

The temperature coefficient of the dielectric constant k is positive and equal to 0·00108 for all frequencies, so that—

$$k_t = k_0 (1 + 0 \cdot 00108\, t).$$

The power factor is constant and equal to 0·007 or 0·008 for all frequencies between 920 p.p.s. and 4,600 p.p.s., and for all temperatures

TABLE VIII.

Dielectric: Manilla paper, not previously dried.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0157 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 3{,}500.$$

Frequency n.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductivity in Bi-mhos per Centimetre Cube σ.
Tested at Air Temperature 18° C.					
920	0·373	0·000834	0·077	0·077	107
2,760	0·675	0·000807	0·048	0·048	193
4,600	0·916	0·000797	0·040	0·040	262
Tested after 1½ *Hours at* 44° C.					
920	0·86	0·000898	0·166	0·164	246
2,760	1·26	0·000832	0·087	0·087	360
4,600	1·38	0·000802	0·060	0·060	394
Tested after 19 *Hours at* 45° C.					
920	0·025	0·000688	0·006	0·006	7
2,760	0·068	0·000686	0·006	0·006	19
4,600	0·120	0·000684	0·006	0·006	34

between 0° C. and 60° C. This shows that for these conditions the phase difference of current and impressed voltage is 89° 36′ for a condenser made with this dry paper. These results prove how exceeding well *very dry* paper is adapted to meet the requirements of a dielectric for insulating telephone cables, in that it has a small dielectric constant, a very high dielectric resistivity, and a small constant value of the ratio S/Cp implying a small power factor. For this dry Manilla paper at 19° C. and 920 p.p.s. the value of $S/C = s$ is 42.

If, however, the Manilla paper was made up into a condenser and tested without previous desiccation the results were very different, and are as shown in Table VIII.

On comparing the results in Table VIII. with those in Table VII. for the dried Manilla paper it will be seen that the undried paper has at 18° C. a value for its conductance and power factor more than

TABLE IX.

Tests of Blotting-paper Condensers.

Frequency n.	Quantity Observed.	Condenser A (Undried Paper).	Condenser B (Dried Paper).	Condenser C (Undried Paper with thin Mica between Sheets).
920	S (in micromhos)	1·21	0·10	1·07
2,760		2·07	0·39	1·93
4,600		2·81	0·79	2·60
920	C (in microfarads)	0·000661	0·000364	0·000636
2,760		0·000587	0·000361	0·000571
4,600		0·000565	0·000362	0·000551
920	S/Cp	0·319	0·005	0·292
2,760		0·204	0·006	0·196
4,600		0·172	0·008	0·164

10 times greater, but that when heated for some time at 45° C. these values fall to those obtained for the previously dried paper.

As it seemed especially important to investigate still farther the effect of moisture an experiment was made with three condensers, the dielectric of which was white blotting-paper. Some sheets of this paper, 12 × 3½ cm., were cut, the thickness of each being 0·021 cm. Condensers were built up with two sheets of blotting-paper interposed between thin copper foil sheets. The ratio of total coated area to thickness of the blotting-paper dielectric was 2,480. One condenser (A) was made with the blotting-paper in its ordinary undried condition, a second one (B) with its blotting-paper carefully dried before and after assembling. It was then kept in a desiccator until tested.

The third condenser (C) was made of blotting-paper in its ordinary

undried condition like (A), but it had a very thin sheet of mica about 0·023 mm. thick interposed between its two sheets of blotting-paper.

These condensers were tested on the bridge as above described, and the values of S, C, and S/Cp determined for three frequencies at 18° C. The results were as shown in Table IX.

It will be seen that careful drying reduces the alternating conductance S, the capacity C, and the ratio S/Cp considerably. On the other hand, the interposition of the thin sheet of mica between the two sheets of paper makes only a very small decrease in these quantities. If we take the numerical values of the alternating-current conductivity S at 18° or 19° C. for these undried and dried papers we can express them in the form $A + Bn$ approximately for various values of the frequency n within telephonic range.

For well-dried Manilla paper at 19° C.—

$$S = 0 + 0{\cdot}000027\, n.$$

For undried Manilla paper at 18° C.—

$$S = 0{\cdot}265 + 0{\cdot}00014\, n.$$

For well-dried blotting-paper at 16° C.—

$$S = 0 + 0{\cdot}00014\, n.$$

For undried blotting-paper at 16° C.—

$$S = 0{\cdot}81 + 0{\cdot}00043\, n.$$

It is seen from Fig. 17 that if the paper is well dried the specific alternating conductivity (σ) is proportional to the frequency, or $\sigma = bn$, within telephonic range. If the paper is undried then a constant term (a) must be added to obtain the conductance, whilst the term (b) is also increased. This suggests that the term (a) depends on electrolytic conduction.

The blotting-paper condensers were then tested with a direct voltage of 25 volts from a battery and the direct-current conductance measured, as usual after 1 minute's electrification, with the galvanometer. We obtained :—

For condenser A (undried) = 0·11 micromhos.
For condenser B (dried) = 0·0002 „
For condenser C (undried, but with mica) = 0·004 micromhos.

Although the numerical values may in this case of direct-current measurement be affected by some error owing to want of perfect contact between the foil plates and the paper, yet they are sufficient to show that the interposition of the mica stops the direct-current conductance, but only careful drying of the paper will reduce the alternating current conductance.

A confirmatory fact, showing that it is moisture which is operative, is that the capacity is much smaller in the case of the dried paper,

whereas the interposition of the thin sheet of mica makes very little difference.

It is quite clear, therefore, that to secure a small value of S/Cp for a paper condenser or paper-insulated cable the paper must be most carefully and thoroughly dried.

The foregoing experiments with dried and undried paper suggested the inquiry whether the increased alternating current conductivity of the damp paper was due to electrolytic conduction or to the presence of conducting particles scattered about in the dielectric and acting merely as metallic conductors.

An experiment was therefore tried which consisted in comparing two condensers both made up with double sheets of white blotting-paper of the same make, but one having very fine metallic particles scattered over the surface between the two sheets of paper so as to make a dielectric consisting of paper with metallic particles distributed through it. We employed very fine silver filings as used for coherers, and also copper powder prepared by reducing the oxide in hydrogen. In both cases blank control condensers were made of the same paper on the same day. These condensers were marked D, E, F, G.

Condenser D was made with double sheets of white blotting-paper plain.
Condenser E was made of the same paper on the same day, but with silver filings scattered between the two sheets of paper.
Condenser F was like D.
Condenser G was made of same paper as F and on the same day, but had copper particles scattered between the two sheets of paper.

These condensers were tested on the bridge with alternating currents of three frequencies for conductance S, capacity C, and power factor S/Cp, and the results were as shown in Table X.

If we compare the results for the condensers E and G, having respectively silver and copper particles scattered between the paper sheets, with the plain paper control condensers D and F, we see that the presence of the metallic particles rather decreases instead of increasing the alternating-current conductivity, capacity, and power factor.

This is probable because of the air-space necessarily introduced by the presence of the metallic particles.

On the other hand, these quantities have the same general magnitude as those found for other condensers of the same kind made with undried paper.

The conclusion is that the increase in alternating conductivity is not due merely to conducting particles disseminated through the dielectric, but to an electrolytic conductivity increased by the presence of moisture particles distributed through the dielectric.

It is clear, therefore, that in the case of paper condensers made for

use with alternating currents the greatest care must be taken to free the paper thoroughly from moisture if the power factor is to be kept low.

TABLE X.

Quantity.	Frequency n.	Condenser D (Plain).	Condenser E (Silver Filings).	Condenser F (Plain).	Condenser G (Copper Filings)
S (in micromhos)	920	0·909	0·633	0·861	0·568
	2,760	1·665	1·120	1·510	1·110
	4,600	2·260	1·570	2·060	1·490
C (in microfarads)	920	0·000620	0·000496	0·000608	0·000500
	2,760	0·000562	0·000451	0·000551	0·000461
	4,600	0·000544	0·000442	0·000538	0·000450
$\frac{S}{Cp}$	920	0·254	0·222	0·246	0·197
	2,760	0·170	0·143	0·158	0·139
	4,600	0·144	0·123	0·133	0·115

TABLE XI.

Dielectric: Paraffined Manilla paper.
(Paper carefully dried before impregnation.)
Approximate Dimensions: Area = 110 sq. cm.
Thickness = 0·0160 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 6{,}900.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	0	0·095	0·002089	0·008	0·008	14
	17	0·091	0·002090	0·008	0·008	13
	48	0·082	0·001998	0·007	0·007	12
2,760	0	0·311	0·002072	0·009	0·009	45
	17	0·282	0·002085	0·008	0·008	41
	47	0·231	0·001993	0·007	0·007	34
4,600	0	0·461	0·002075	0·008	0·008	67
	17	0·529	0·002073	0·009	0·009	77
	45	0·438	0·001997	0·008	0·008	63

These results naturally led to an examination of the same paper when impregnated with paraffin wax. A condenser was prepared of carefully dried Manilla paper impregnated with paraffin wax by

immersing it for some time in the molten wax. The results of measurements are shown in Table XI.

It is seen that the power factor, or value of S/C*p*, is constant for all temperatures and frequencies, as in the case of the plain, well-dried unimpregnated paper. If, however, the paper was impregnated before drying it, then the results shown in Table XII. were obtained. The value of S/C*p* and of S increases with temperature, whilst S increases as usual with frequency, and S/C*p* diminishes with frequency at the same temperature.

The plotting of the results in the last two tables is shown in Fig. 18, and is very instructive. It is clear that the presence of moisture in the

TABLE XII.

Dielectric: Paraffined Manilla paper.
(Paper not dried before impregnation.)
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0242 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 2{,}270.$$

Frequency n.	Centi-grade Tempe-rature T.	Conduct-ance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	0	0·095	0·000965	0·017	0·017	42
	19	0·230	0·000916	0·043	0·043	101
	41	0·633	0·000995	0·110	0·110	279
2,760	0	0·233	0·000955	0·014	0·014	103
	19	0·454	0·000899	0·029	0·029	200
	42	1·230	0·000965	0·074	0·074	542
4,600	0	0·368	0·000951	0·013	0·013	162
	19	0·639	0·000887	0·025	0·025	281
	41	1·610	0·000944	0·059	0·059	709

dielectric always increases the value of S/C*p*, or of the power-factor, and increases it more in proportion as the frequency is lower. The values of the conductivity (σ) are plotted in Fig. 19 for various temperatures in terms of the frequency. It will be seen that the presence of moisture immensely affects the conductivity.

To determine the influence of the paraffin *per se* we constructed a condenser consisting of 8 plates of pure paraffin wax cast about 0·5 cm. thick and 100 sq. cm. in area. These plates had tinfoil sheets interposed, and were built up into a solid condenser of pure paraffin wax. The condenser was tested on the bridge, and the results obtained are shown in Table XIII.

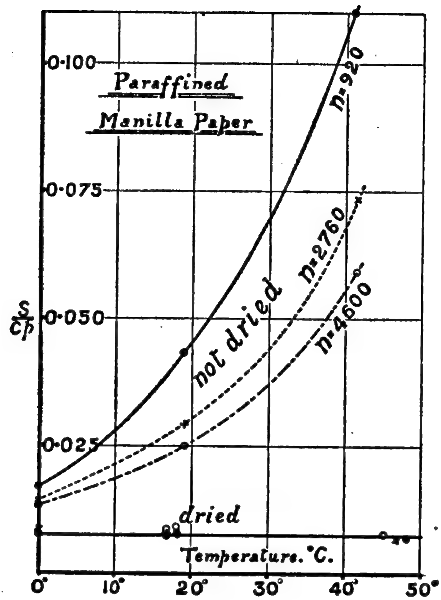


FIG. 18.—Values of $\frac{S}{Cp}$ for various Temperatures and Frequencies for Condensers made with Paraffined Manilla Paper, Dried and Undried.

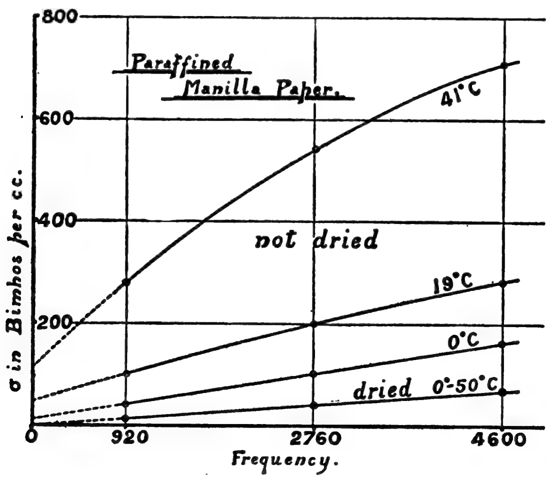


FIG. 19.—Variation of Conductivity with Temperature and Frequency for Paraffined Manilla Paper, Dried and Undried.

It is seen that the value of S/Cp is very small and almost independent of frequency and temperature.

We can check the general accuracy of the above figures by noticing that the capacity measurement, viz., 310 micro-microfarads, gives us by equation (36) the value of the dielectric constant k as follows—

$$k = \frac{310 \times 11{\cdot}3}{1{,}480} = 2{\cdot}3.$$

This is in good agreement with known values of the dielectric constant of paraffin wax.

From equation (37) and the results in Table XII. we can obtain

TABLE XIII.

Dielectric: Paraffin wax.
Approximate Dimensions: Area = 800 sq. cm.
Thickness = 0·54 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}480.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	17	0·0006	0·000310	0·0003	0·0003	0·4
	27	0·0007	0·000310	0·0004	0·0004	0·5
2,760	17	0·003	0·000311	0·0005	0·0005	2·0
	27	0·003	0·000310	0·0006	0·0006	2·0
4,600	17	0·005	0·000311	0·0005	0·0005	3·4
	27	0·007	0·000309	0·0008	0·0008	4·7

approximately the resistivity of paraffin for alternating currents of the three frequencies; at 17° C. and at 920 p.p.s. it is—

$$\rho = \frac{1480}{0{\cdot}0006} = 2{\cdot}47 \times 10^6 \text{ megohms per centimetre cube.}$$

The resistivity of paraffin wax for direct currents was found by Ayrton and Perry to be $3{\cdot}4 \times 10^{10}$ megohms per centimetre cube "after several minutes' electrification," and in any case is a number of the order of 10^{10} megohms per centimetre cube.* Hence it is clear that even paraffin has a far greater conductivity for alternating than for direct currents, and that it affects very little the good qualities of paper carefully dried and impregnated with it.

* W. E. Ayrton and J. Perry, "The Viscosity of Dielectrics," *Proceedings of the Royal Society*, vol. 27, p. 239, 1878.

It was then interesting to discover how far the results actually obtained in practice with paper as a dielectric agree with the foregoing conclusions. Accordingly a length of paper-insulated dry-core telephone cable was obtained from the British Insulated and Helsby Cable Company of Prescot. This cable consisted of a pair of copper wires, each 0·635 mm. in diameter (No. 23 or 24 S.W.G.), each wrapped

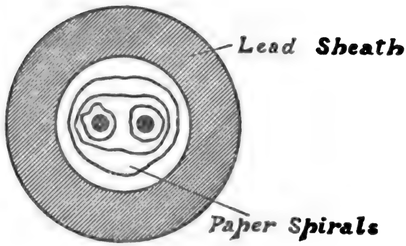


FIG. 20.—Section of Dry Core Cable.

with twisted paper, and the two included in a lead covering (Fig. 20). Such cable is technically known as dry-core cable, 10 lbs. to the mile, and its listed capacity for telephone frequencies is 0·05 microfarad per mile. We tested 30 yards of it on our bridge and obtained the results shown in Table XIV.

It is seen that the conductance is almost independent of temperature at the lowest frequency, but rises with frequency for the same tempera-

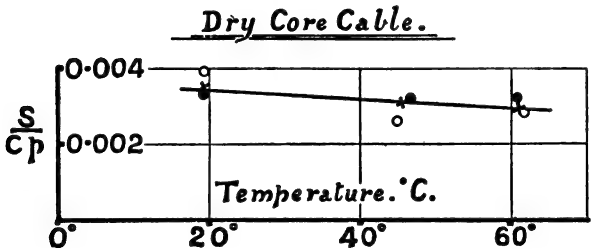


FIG. 21.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for Dry Core Paper Insulated Cable.

Note.—Observations for 920 p.p.s. represented by black dots; ditto for 2,760 p.p.s. by crosses and for 4,600 by circles.

ture and decreases slightly with rise of temperature at the higher frequency. The value of S/C*p* and of the power factor is constant and independent both of frequency and temperature, and is less than one-third of 1 per cent. The fact that S/C*p* is even less than for dry Manilla paper is accounted for by the air-spaces in the paper insulation of the dry-core cable.

The capacity measurements in the following table for the 30 yards of cable are equivalent to 0·054 microfarad per mile, which is in accordance with practical experience.

The dielectric conductance per mile is 1·06 micromhos, calculated from our values in Table XIII. The reciprocal of this is 0·94 megohms per mile, which is of the usual order of magnitude for this dry-core cable.

At a frequency of 920 the value of S/C for this cable is 19·34, and 17·36 for a frequency 800, or for $p = 2\pi n = 5{,}000$.

TABLE XIV.

Paper-insulated Dry-core Telephone Cable.

Single pair of conductors.
Diameter of conductor = 0·635 mm. = 10 lbs. per mile.
Distance apart of conductors (centre to centre) = 1·5 mm. about.
Thickness of lead covering = 1·6 mm.
Overall diameter of cable = 7·9 mm.
Length of cable tested = 30 yards.

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.
920	19	0·018	0·000931	0·003	0·003
	46	0·017	0·000924	0·003	0·003
	61	0·017	0·000930	0·003	0·003
2,760	19	0·057	0·000931	0·004	0·004
	45	0·049	0·000921	0·003	0·003
	61	0·047	0·000930	0·003	0·003
4,600	19	0·104	0·000929	0·004	0·004
	45	0·069	0·000923	0·003	0·003
	62	0·075	0·000929	0·003	0·003

Since the value of S/C is about 120 for a gutta-percha twin-wire cable at 800 p.p.s., we see what a very great advantage telephonically is gained by the use of air-paper insulation for lead-covered underground cables.

The variation of S/Cp with temperature and frequency for this dry-core cable is graphically delineated by the line in Fig. 21.

The conductance in micromhos per mile of this cable for any frequency n within the telephonic range can be approximately calculated by the formula—

$$S = 0·001173\ n.$$

The capacity is practically independent of frequency and temperature.

and equal to 0·054 microfarads per mile, whilst S/C for a frequency n is 0·0217 n.

IV. Mica.

A condenser was made up, as usual, of very thin sheets of mica with tinfoil sheets interposed. The ratio of total area to thickness was 7,200. This was tested on the bridge, and the epitomised results are shown in Table XV.

It will be seen that the conductance increases with the frequency as with other dielectrics, and also with the temperature, and the

Table XV.

Dielectric: Mica.
Approximate Dimensions: Area = 37 sq. cm.
Thickness = 0·0051 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 7{,}200.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	16	0·017	0·002460	0·001	0·001	2·4
	40	0·022	0·002510	0·002	0·002	3·1
	64	0·036	0·002550	0·003	0·003	5·0
	88	0·039	0·002570	0·003	0·003	5·4
2,760	16	0·053	0·002470	0·001	0·001	7·4
	40	0·064	0·002510	0·002	0·002	8·9
	64	0·066	0·002550	0·002	0·002	9·2
	88	0·081	0·002570	0·003	0·003	11·3
4,600	16	0·144	0·002460	0·002	0·002	20·0
	40	0·102	0·002520	0·001	0·001	14·2
	63	0·211	0·002550	0·003	0·003	29·3
	88	0·217	0·002570	0·003	0·003	30·1

capacity increases slowly also, and likewise the value of S/Cp, or the power factor. Owing to the small value of S/Cp it is rather difficult to determine the quantities with the same accuracy as for other dielectrics.

The values of S/Cp in terms of frequency plot out into practically straight lines almost coincident, as shown in Fig. 22.

If we calculate by formula (36) the value of the dielectric constant for 920 p.p.s. and 16° C. we obtain a number close to 4·0. The observed values for the dielectric constant of mica, as given in text-books, vary from 4 to 8, probably depending on the amount of oxide of iron

present. Hence our capacity measurements are probably correct. Moreover, the capacity increases slowly with the temperature. The temperature coefficient for a frequency of 920 p.p.s. between 16° C. and 88° C. is nearly 0·062 per cent. Hence the dielectric constant at t° C., in terms of that at 0° C., is nearly given by—

$$k_t = k_0\,(1 + 0{\cdot}00062\,t).$$

Owing to the small values of S/Cp it is not possible to determine the value of the specific conductivity very accurately.

At 40° C. the values of the conductance S plot out in terms of the frequency into a nearly straight line represented by—

$$S = 0{\cdot}002 + 0{\cdot}000022\,n$$

and the conductivities (σ) for the three frequencies used are respectively 3·0, 9·0, and 14·2 bi-mhos.

The other values of S do not give very straight lines, but they are sufficient to show that mica is quite normal in having a very small

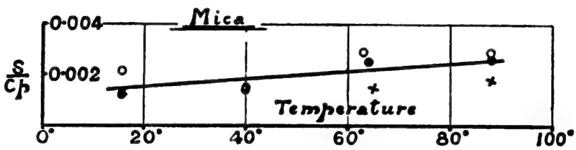


FIG. 22.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for Mica Condenser.

conductivity for direct currents, but a conductivity for alternating currents, which can be approximately represented by a function of the form $\sigma = a + b\,n$, where a is a very small quantity.

V. EBONITE.

A condenser was made up with thin sheets of ebonite with tinfoil between as described for the other dielectrics and tested in the same manner at three frequencies and various temperatures. The conductance, capacity, and power factor for the condenser are given in Table XVI. It will be seen that the conductance increases with the frequency as usual at constant temperature, and at constant frequency it increases with the temperature at first slowly and then more rapidly. The capacity also increases with the temperature. The value of S/Cp increases with the temperature, but is the same at the three frequencies at identical temperatures. Accordingly it is not affected by frequency, but is by temperature.

The curve representing the variation of S/Cp with temperature for ebonite is given in Fig. 23. It rises rapidly with temperature, but is the same for the three frequencies.

The capacity of the condenser at 19° C. is 292 micro-microfarads, and the dimension ratio of area/thickness is 1,040. Hence the dielectric

constant (k) of this ebonite for alternating currents of frequency between 920 and 4,600 is given by $k = \frac{11{\cdot}3 \times 292}{1040} = 3{\cdot}17$, which agrees fairly well with the values obtained by direct currents. The dielectric resis-

Table XVI.

Dielectric: Ebonite.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0529 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}040.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	0	0·006	0·000280	0·004	0·004	6
	19	0·007	0·000292	0·005	0·005	7
	46	0·027	0·000301	0·015	0·015	26
	60	0·107	0·000340	0·055	0·055	103
	84	0·167	0·000403	0·072	0·072	161
2,760	0	0·020	0·000279	0·004	0·004	19
	19	0·027	0·000290	0·005	0·005	26
	45	0·074	0·000298	0·014	0·014	71
	63	0·284	0·000332	0·049	0·049	273
	84	0·480	0·000392	0·071	0·071	461
4,600	0	0·033	0·000279	0·004	0·004	32
	19	0·045	0·000289	0·005	0·005	43
	44	0·120	0·000298	0·014	0·014	115
	62	0·420	0·000327	0·044	0·044	404
	83	0·808	0·000380	0·074	0·074	778

tivity (ρ) at 19° C. for a frequency 920 in megohms per centimetre cube is given by—

$$\rho = \frac{1040}{0{\cdot}007} = 150{,}000 \text{ (nearly)}.$$

An examination of the values given for S in Table XV. shows that the conductance of ebonite for different frequencies (n) can be approximately represented by a function of the form A + Bn. The quantity A proves to be very small. The observed conductance can be expressed as follows:—

At 0° C. ... ... $S = 0 + 0{\cdot}000007\,n$
„ 19° C. ... ... $S = 0 + 0{\cdot}00001\,n$
„ 45° C. ... ... $S = 0{\cdot}004 + 0{\cdot}000024\,n$
„ 60° C. ... ... $S = 0{\cdot}006 + 0{\cdot}000092\,n$
„ 84° C. ... ... $S = 0{\cdot}007 + 0{\cdot}00017\,n$

The values of the alternating conductivity σ are plotted in terms of frequency and temperature in Fig. 24. It will be seen that they are

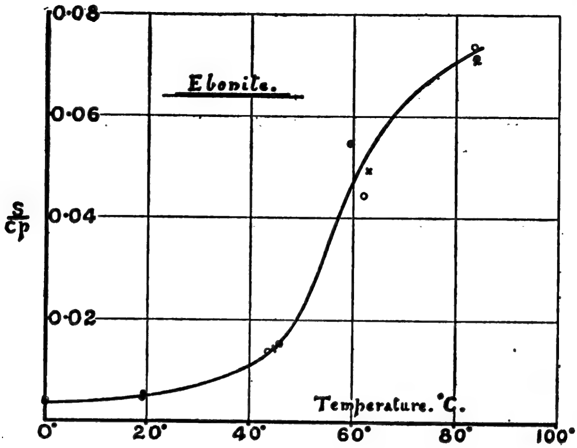


FIG. 23.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for an Ebonite Condenser.

Note.—Black dots denote 920, crosses 2,760, and small circles 24,600 p.p.s.

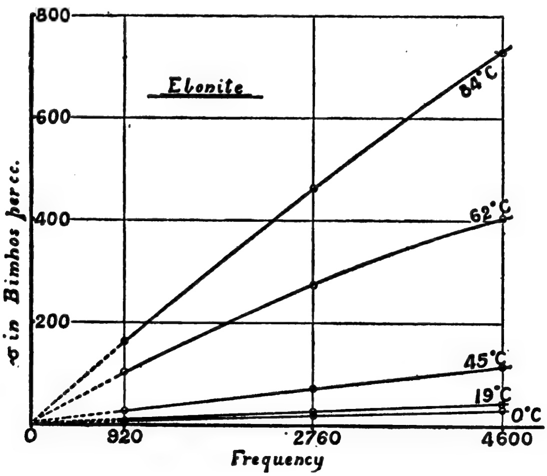


FIG. 24.—Variation of Conductivity with Temperature and Frequency for Ebonite.

straight lines converging to the origin. Hence $\sigma = b\,n$ nearly for ebonite.

At a frequency of 920 p.p.s. the dielectric constant of ebonite at

any temperature t between 0° C. and 84° C. can be represented by the formula—

$$k_t = k_0 (1 + 0\cdot00523\, t).$$

It has therefore a larger temperature coefficient than glass, but about the same as celluloid.

VI. Pure Indiarubber.

The next dielectric examined was unvulcanised para indiarubber. It was furnished to us in sheet by the Indiarubber, Gutta-percha and

Table XVII.

Dielectric : Pure Para Indiarubber.
Approximate Dimensions : Area = 73 sq. cm.
Thickness = 0·0556 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}310.$$

Frequency n.	Centi-grade Tempe-rature T.	Conduc-tance in Micromhos S	Capacity in Microfarads C	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ
920	0	0·005	0·000308	0·003	0·003	4
	18	0·009	0·000301	0·005	0·005	7
	30	0·010	0·000299	0·006	0·006	8
	43	0·016	0·000300	0·009	0·009	12
2,760	0	0·014	0·000306	0·003	0·003	11
	18	0·024	0·000302	0·005	0·005	18
	30	0·024	0·000299	0·005	0·005	18
	44	0·037	0·000298	0·007	0·007	28
4,600	0	0·022	0·000307	0·003	0·003	17
	18	0·037	0·000300	0·004	0·004	28
	30	0·031	0·000298	0·004	0·004	24
	44	0·058	0·000299	0·007	0·007	44

Telegraph Company, Ltd., and made up into a plate condenser of our standard size. Owing to the compressibility of this material it is not easy to determine the dimension ratio or ratio of total dielectric section to dielectric thickness, but the number 1,310 is not far from the truth. The results of tests are shown in Table XVII. It will be seen that for this dielectric as for ebonite the ratio S/Cp is nearly independent of frequency, but increases with the temperature. The alternating dielectric conductance S increases with the temperature rather rapidly, but the capacity diminishes very slightly with rise of temperature.

The conductance can be expressed within the limits of frequency

employed in telephony approximately by a function of the form A + B n, where n is the frequency and A and B are coefficients, which increase with the temperature. We have—

At 0° C.	$S = 0.001 + 0.0000043\,n$
„ 18° C.	$S = 0.002 + 0.0000076\,n$
„ 30° C.	$S = 0.003 + 0.0000076\,n$
„ 43° C.	$S = 0.0055 + 0.0000114\,n$

Hence the coefficient A is small as in the case of all good insulators. The temperature variation of the capacity is small or even slightly negative. The alternating dielectric constant for a frequency 920 and at 18° C. is $\frac{11.3 \times 301}{1310} = 2.6$. It is almost independent of frequency.

The variation of S/Cp with temperature and frequency is shown in the curves in Fig. 25. The curves are in contact at 0° C., and separate slightly with rise in temperature. The conductivities (σ) are plotted in terms of the frequency and for different temperatures in Fig. 26.

VII. Vulcanised Indiarubber.

Sheets of good vulcanised indiarubber, obtained from the India-rubber, Gutta-percha, and Telegraph Company, Ltd., were cut to our standard size and formed with tinfoil into a condenser. The ratio of total cross section to thickness of dielectric was as nearly as could be measured 1,030. The condenser was tested on the bridge at the usual three frequencies, and at various temperatures between — 14° C. and 83° C.

The results are given in the following Table XIX., and the values of the ratio S/Cp in terms of the frequency are delineated in the curves in Fig. 27 for various temperatures. It will be seen that they differ in a very remarkable manner from the curves for S/Cp of all the other dielectrics (see Table XIX.).

Whereas for all other dielectrics the ratio S/Cp or the power factor is either constant, or else increases with the temperature and decreases with the frequency, for vulcanised indiarubber it is found that each of the curves delineating the variation of S/Cp with temperature and for a constant frequency is concave upwards. Hence there is a certain temperature for which the power factor is a minimum, and this temperature is near the normal temperature of the air. Moreover, the curves all cross at this point, so that at normal temperature the power factor is not merely a minimum, but it is independent of frequency.

A still further peculiarity of vulcanised indiarubber is that the temperature coefficient of the capacity is negative for the range of frequency and of temperature we have employed. Hence the dielectric constant k_t at any temperature t is connected with the value k_0 at 0° C by the formula—

$$k_t = k_0 (1 - a\,t),$$

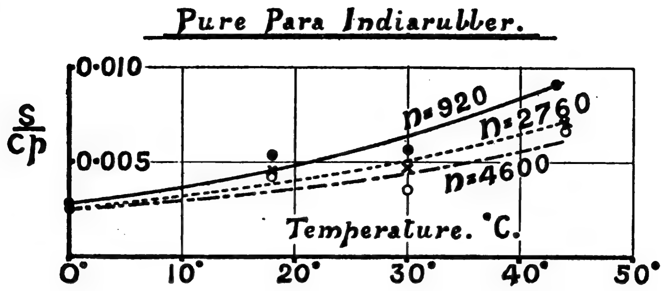


FIG. 25.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for Unvulcanised Indiarubber Condenser.

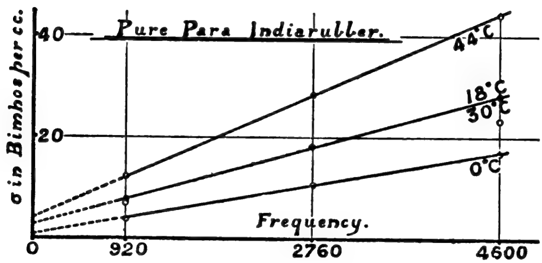


FIG. 26.—Variation of Conductivity for Unvulcanised Indiarubber with Temperature and Frequency.

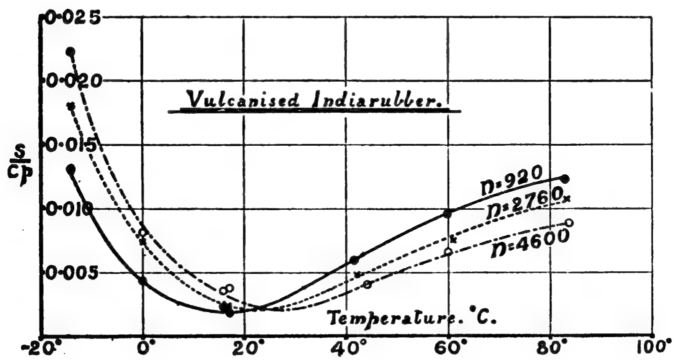


FIG. 27.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for Vulcanised Indiarubber Condenser.

where a has the values—

$$a = 0{\cdot}0015 \text{ for a frequency of } 920$$
$$a = 0{\cdot}0013 \quad " \quad " \quad 2{,}760$$
$$a = 0{\cdot}0014 \quad " \quad " \quad 4{,}600$$

The dielectric constant at 17° C. and for all frequencies has a value close to 2·73.

For such a mode of variation of S/Cp it is obviously impossible to find any simple linear formula of the type $A + Bn$ for the conductance S which will fit all points of temperature, seeing that below 17° C. the temperature coefficient of S/Cp reverses sign. Nevertheless, we find that for this vulcanised rubber condenser we have for the conductance S the values at 41° C.—

TABLE XIX.

Dielectric: Vulcanised Indiarubber.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0534 cms.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}030.$$

Frequency n.	Centigrade Temperature T	Conductance in Micromhos S	Capacity in Microfarads C	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ
920	−14	0·019	0·000254	0·013	0·013	19
	0	0·007	0·000254	0·004	0·004	7
	17	0·003	0·000249	0·002	0·002	3
	41	0·008	0·000233	0·006	0·006	8
	60	0·012	0·000231	0·010	0·010	12
	83	0·016	0·000230	0·012	0·012	16
2,760	−14	0·078	0·000252	0·018	0·018	76
	0	0·032	0·000252	0·007	0·007	31
	17	0·010	0·000247	0·002	0·002	10
	42	0·019	0·000232	0·005	0·005	18
	61	0·030	0·000231	0·008	0·008	29
	83	0·042	0·000228	0·011	0·011	41
4,600	−14	0·162	0·000251	0·022	0·022	158
	0	0·059	0·000252	0·008	0·008	57
	17	0·027	0·000247	0·004	0·004	26
	44	0·027	0·000232	0·004	0·004	26
	60	0·044	0·000230	0·007	0·007	43
	84	0·059	0·000227	0·009	0·009	57

$$S = 0{\cdot}003 + 0{\cdot}0000055\,n\,;$$

and from 61° to 83° C. we have approximately—

$$S = 0{\cdot}004 + 0{\cdot}0000087\,n.$$

The constant A is therefore very small or else zero, as it is in the case of all good insulators. The values of the conductivities (σ) for the three frequencies and for various temperatures are set out in curves in Fig. 28.

In connection with this abnormality of vulcanised indiarubber in regard to its apparent decrease in dielectric constant with rise of temperature it may be recalled that the same substance is abnormal with respect to the effect of heat upon it, in that it contracts with rise of temperature instead of expanding. Hence, over a certain range, at least, its coefficient of linear expansion with heat is negative.

It would be interesting to learn if any other observers have noted a negative temperature coefficient for the dielectric constant of vulcanised

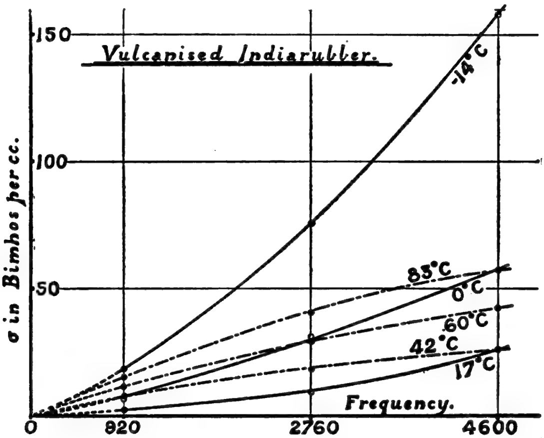


FIG. 28.—Variation of Conductivity with Temperature and Frequency for Vulcanised Indiarubber.

indiarubber. In all other cases our observations have shown a positive temperature coefficient, and this deviation does not appear to be due to errors of experiment. It would be interesting to know if telephonic engineers, or cable manufacturers, have any information on this subject.

VIII. Gutta-percha.

We have in the next place to consider the important dielectric gutta-percha, especially interesting because it is the only dielectric which can be employed for insulating submarine cables. It was, in fact, owing to an answer made in reply to a question put by one of us in the discussion on a recent paper by Major O'Meara, on "Submarine Cables for Long-distance Telephone Circuits," * concerning gutta-

* W. A. J. O'Meara, *Journal of the Institution of Electrical Engineers*, vol. 46, p. 357, 1911.

percha, that we were led to undertake the experiments recorded in the present paper.

It has long been known to telephonic engineers that a gutta-percha insulated cable possesses an effective dielectric conductance for alternating-currents far greater than its direct-current conductance, as measured in the usual way. It was the desire to explore this matter more completely that instigated the present research.

TABLE XX.

Dielectric: Gutta-percha.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0582 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 945.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S	Capacity in Microfarads C	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ
920	−14	0·021	0·000219	0·017	0·017	22
	0	0·031	0·000228	0·024	0·024	33
	15	0·028	0·000239	0·020	0·020	30
	19	0·019	0·000244	0·014	0·014	20
	27	0·009	0·000241	0·007	0·007	10
	50	0·004	0·000240	0·003	0·003	4
2,760	−14	0·050	0·000216	0·014	0·014	53
	0	0·086	0·000225	0·022	0·022	91
	15	0·092	0·000237	0·023	0·023	97
	19	0·082	0·000243	0·020	0·020	87
	27	0·043	0·000239	0·010	0·010	46
	50	0·013	0·000239	0·003	0·003	14
4,600	−14	0·076	0·000215	0·012	0·012	80
	0	0·138	0·000224	0·021	0·021	146
	15	0·167	0·000236	0·025	0·025	177
	19	0·154	0·000239	0·022	0·022	163
	27	0·092	0·000237	0·013	0·013	97
	50	0·030	0·000239	0·004	0·004	32

Our first experiments on gutta-percha were made with some thin sheet gutta-percha supplied to us by the Indiarubber, Gutta-percha, and Telegraph Company, Ltd. This was made up with tinfoil into a plate condenser of our standard size, and the ratio of coated surface to thickness of dielectric was as nearly as could be determined 945. This condenser was tested at the usual three frequencies, and at various temperatures between −14° C. and 50° C. on our bridge, and the epitomised results are recorded in Table XX., and graphically in Figs. 29 and 30.

It will be seen from Table XX. that although the variation of capacity with temperature is normal, in that it increases with tempe-

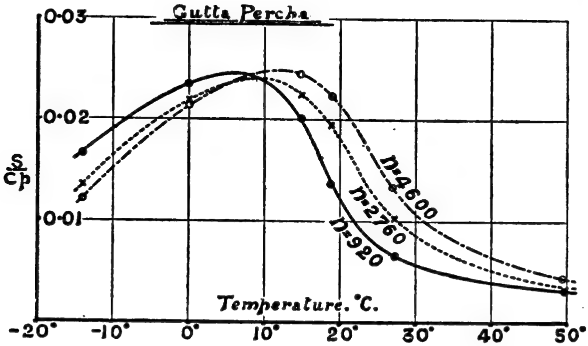


FIG. 29.—Variation of $\frac{S}{Cp}$ (Power Factor) with Temperature and Frequency for Gutta-percha Condenser.

rature, the variation of the ratio S/Cp and of the conductivity σ is extremely abnormal.

The power factor varies with the temperature, but has a maximum value near 10° C. (see Fig. 29), at or about which temperature it is

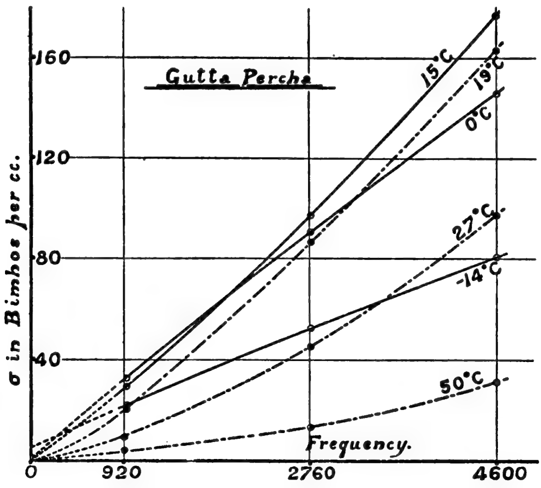


FIG. 30.—Variation of Conductivity with Temperature and Frequency for Gutta-percha.

nearly the same for each value of the frequency we have used. The curves representing the variation of S/Cp with temperature intersect at or near 10° C. These power-factor curves for gutta-percha exhibit a

quality the reverse of the similar curves for vulcanised indiarubber in that they are convex upwards instead of downwards. Accordingly rather above 20° C. the temperature coefficient of the power factor is negative, but below that temperature it is positive. The general form of this power-factor curve for gutta-percha has been confirmed by independent measurements made by two observers and with two or three different gutta-percha condensers. The fact that the temperature coefficient for the energy loss in a gutta-percha insulated cable at a frequency of 50 p.p.s. is negative above 10° C. was mentioned by Mr. Rayner in the discussion on Major O'Meara's paper above mentioned.*

The same quantity was also found to be negative by Mr. Campbell at a frequency of 800 p.p.s. Neither of these observers, however, appear to have noticed that this is merely a consequence of the fact that the curve representing the variation of S/Cp with temperature for any frequencies in the case of gutta-percha is a curve, convex upwards, and therefore has a maximum value, which maximum value occurs about the ordinary atmospheric temperature. It is therefore a very extraordinary thing that the power factor for the whole range of telephonic frequency should have a minimum value in the case of vulcanised indiarubber and a maximum value in the case of gutta-percha at or about normal atmospheric temperature. The maximum value of the power factor for gutta-percha is about 2·5 per cent., but the minimum value for vulcanised indiarubber is not one-tenth part of this; in fact, only 0·2 per cent.

[Since this paper was sent in we have tested the vulcanised indiarubber at lower temperatures, and found that it has a maximum value for its power factor at −30° C. See Appendix for results.]

In consequence of this abnormal variation of S/Cp or the power factor, it is impossible to express over a wide range by any simple linear formula the dielectric conductance in terms of the frequency. The value of the conductivity (σ) in terms of the frequency and temperature are delineated in Fig. 30. The variation of capacity and therefore of dielectric constant with temperature is, however, quite normal, and increases with temperature for different frequencies in accordance with the law $k_t = k_0(1 + a\,t)$, where—

$$a = 0{\cdot}00105 \text{ for } 920 \text{ p.p.s.}$$

and—

$$a = 0{\cdot}00124 \text{ for } 2{,}760 \text{ p.p.s.}$$

and—

$$a = 0{\cdot}00134 \text{ for } 4{,}600 \text{ p.p.s.}$$

over a range of temperature between 0° C. and 80° C.

The dielectric constant at 15° C. for alternating currents of the frequency used is given by the rule—

$$k = \frac{11{\cdot}3 \times 237}{945} = 2{\cdot}83.$$

* W. A. J. O'Meara, *Journal of the Institution of Electrical Engineers*, vol. 46, p. 412, 1911.

This value is certainly lower than that for direct currents or steady electric force. In this last case the text-books give values varying from 3·5 to 7.

Having regard to the considerable effect of moisture in paper

Table XXI.

Dielectric: Gutta-percha.
(Dried at 50° C. for some hours.)
Approximate Dimensions: Area = 110 sq. cm.
Thickness = 0·0582 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}890.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	16	0·052	0·000490	0·019	0·019	28
2,760	16	0·185	0·000484	0·022	0·022	98
4,600	16	0·318	0·000481	0·023	0·023	168

Table XXII.

Dielectric: Gutta-percha.
(Soaked in water at 50° C. for some hours and then dried.)
Approximate Dimensions: Area = 110 sq. cm.
Thickness = 0·0582 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}890.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	16	0·060	0·000475	0·022	0·022	32
2,760	16	0·194	0·000468	0·024	0·024	103
4,600	16	0·330	0·000465	0·025	0·025	175

dielectric upon the value of the power factor, it was considered desirable to test carefully dried gutta-percha sheets against the same sheet after it had been soaked in water for some time and then wiped dry. The experiments recorded in Tables XXI. and XXII. were there-

fore tried, and, as will be seen, the gutta-percha which had been soaked for some time exhibits a slightly higher value for the conductivity and also for the power factor.

We then conducted some tests on ordinary gutta-percha insulated cables. Two samples were prepared for us by the Indiarubber, Gutta-percha and Telegraph Company, Ltd., one consisting of a single pair of gutta-percha-covered copper wires packed up with impregnated hemp to complete the space and then braided over to make a cable

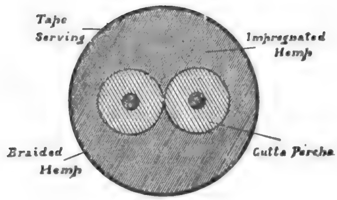


FIG. 31.—Section of Gutta-percha Cable with Pair of Twisted Wires.

(Fig. 31). The other sample was a twin-wire cable and consisted of a pair of similar copper wires, but both embedded in the same gutta-percha covering, the centres of the wires being 0·24 cm. apart (Fig. 32). The copper wires were in both cases No. 18 S.W.G. size and 1·22 mm. or 0·048 in. in diameter.

In the case of the single pair of wires a length of 31 yards sufficed for our measurements, and in the case of the twin wire 50 yards. The cables were measured both stretched out straight and also coiled; but as the cables were not lead covered their condition when coiled was

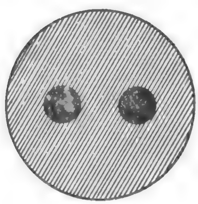


FIG. 32.—Section of Twin-wire Gutta-percha Cable.

such as to alter both the capacity and effective conductance. The values therefore which should be taken are those which belong to the cable when tested laid out straight.

The results of tests are gathered together in Tables XXIII. and XXIV. The first thing which will be noticed is the degree to which the power factor of the single-pair cable exceeds that of the twin-wire cable, being nearly 4 times greater. A little consideration showed, however, that this is only what might be expected from the nature of the path of

the lines of electric strain between conductor and conductor. In the case of the twin-wire cable this path is almost wholly in the gutta-percha insulator, and accordingly in testing the wire to wire leakance and capacity we are testing what is virtually a condenser having a dielectric made of gutta-percha only. In the case of the pair wire the path of the electric flux is partly through gutta-percha and partly through impregnated damp hemp with air-spaces between. Hence the

TABLE XXIII.

Single-pair Gutta-percha Cable (Fig. 31).

Diameter of conductors = 0·122 cm.
Each conductor separately insulated with gutta-percha to a diameter = 0·45 cm.
The pair then made up with a filling of impregnated hemp to a diameter = 1·27 cm., and covered with braided hemp.
Length of cable = 31 yards.

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.
		Cable laid out Straight.			
920	17	1·54	0·002570	0·106	0·105
2,760	16	5·15	0·002360	0·126	0·125
4,600	16	8·11	0·002260	0·124	0·123
		Cable Coiled.			
920	16	1·75	0·002780	0·109	0·108
2,760	16	5·24	0·002540	0·119	0·118
4,600	16	8·11	0·002460	0·114	0·113

dielectric between wire and wire is a non-homogeneous material, being partly gutta-percha, partly hemp, tar, water, and other substances.

Having regard to the manner in which the presence of moisture has been proved by our previous experiments to increase the dielectric power factor, it is not at all surprising to find that whereas in the case of the pair-wire cable the power factor is over 10 per cent. it is under 3 per cent. in the case of the twin-wire cable; also, that the effective

conductance is much greater in the case of the former cable even for a shorter length. This view is confirmed by noticing that when reduced to equal lengths of cable the wire-to-wire capacity is much greater for the pair-wire cable than for the twin wire, though the wires are the same size and farther apart in the case of the pair of wires. Again, it will be noticed that in the case of the twin-wire cable where the dielectric is nearly all gutta-percha, the power factor at 16° C. is independent of the frequency, which is characteristic of gutta-percha as a dielectric at this temperature. On the other hand, for the pair wire

TABLE XXIV.

Twin-wire Gutta-percha Cable (Fig. 32).

Diameter of conductors = 0·122 cm.
Distance apart of conductors = 0·25 cm., centre to centre.
Overall diameter of gutta-percha insulation = 0·64 cm.
Length of cable = 50 yards.

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads. C.	$\frac{S}{Cp}$	Power Factor.
Cable stretched out Straight.					
920	16	0·479	0·002840	0·029	0·029
2,760	16	1·413	0·002780	0·029	0·029
4,600	16	2·270	0·002760	0·029	0·029
Cable Coiled.					
920	16	0·876	0·003630	0·042	0·042
2,760	16	2·860	0·003520	0·047	0·047
4,600	16	4·910	0·003460	0·049	0·049

where the dielectric is non-homogeneous and contains moisture the power factor increases with the frequency, which is a characteristic of dielectrics containing moisture. Hence, for telephone cables we see the importance of embedding both lead and return wires in the same gutta-percha covering, and not using ordinary undried impregnated hemp as packing between separate gutta-percha insulated wires merely laid together.

An additional matter of practical interest in connection with gutta-

percha is the value of the ratio S/C for different frequencies at ordinary temperature. From Table XX. it is seen that at 16°C. we have—

$$S/Cp = 0{\cdot}020 \text{ for } 920 \text{ p.p.s.}$$
$$S/Cp = 0{\cdot}023 \quad ,, \quad 2{,}760 \quad ,,$$
$$S\,Cp = 0{\cdot}025 \quad ,, \quad 4{,}600 \quad ,,$$

The value of $p = 2\pi n$ is 5,777, 17,333, and 28,885 for the three frequencies. Hence the values of S/C are respectively 117, 389, and 708 for the above three frequencies. The value for the standard telephonic frequency—viz., $p = 5{,}000$—should therefore be not far from 100. In the case of the twin-wire gutta-percha cable tested by us we found that $S/Cp = 0{\cdot}029$ at 16° C. and 920 p.p.s. This would give $S/C = 167$ for 920 p.p.s. and 145 for the standard frequency.

It is interesting to note that for the Anglo-French (1910) loaded English Channel telephone (4-wire) cable Mr. Jacob gave the value of S/C as 114 at 750 p.p.s. in the discussion on Major O'Meara's paper.*

Since $2\pi \times 750 = 4{,}725$ and $114/4{,}725 = 0{\cdot}024 = S/Cp$, the value given by Mr. Jacob for S/C for this cable, is equivalent to a power factor of 2·4 per cent., which is not very far from the value obtained by us for the gutta-percha twin-wire cable. Messrs. Campbell and Eckersley, in an article on "The Insulation of Inductive Coils," † give a few measurements of the dielectric resistance of a gutta-percha wire for alternating currents of various frequencies. They do not give the values of S/Cp, but these can be calculated from their figures, which are as follows:—

Frequency. $= n$.	Capacity in Microfarads $=$ C.	Dielectric Resistance in Megohms $= 1/S$.	Calculated Value of S/Cp.
200	0·00692	1·033	0·110
1,000	0·00650	0·325	0·075
2,000	0·00631	0·105	0·120

These measurements were made by the Wien series bridge method, presumably at atmospheric temperatures, but the values are too high for pure gutta-percha, for which the ratio S/Cp is certainly not far from 0·025 at 16° C. The above facts with regard to the dielectric conductance and power factor of gutta-percha are of great importance in connection with its use for insulating submarine telegraph and telephone cables. Having regard to the influence of S/C upon the attenuation constant it is certainly unfortunate that gutta-percha, which

* W. A. J. O'Meara, *Journal of the Institution of Electrical Engineers*, vol. 46, p. 418, 1911.

† A. Campbell and J. L. Eckersley, *Electrician*, vol. 64, p. 351, 1909.

is unique in its qualities as a cable insulator, should be unique also in possessing a large maximum value for its alternate-current dielectric conductivity at or about ordinary temperatures. If vulcanised india-rubber could be used instead it would, in this respect, have great advantages. If any way could be found of employing dry paper as the effective dielectric for submarine cables there is no question that a great improvement in transmission qualities for telegraphy and telephony would result.

TABLE XXV.

Dielectric: Slate (after prolonged drying).
Approximate Dimensions: Area = 18·3 sq. cm.
Thickness = 0·21 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 88.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	0	0·046	0·000111	0·072	0·072	530
	17	0·050	0·000100	0·086	0·086	570
	36	0·070	0·000109	0·110	0·110	800
	54	0·064	0·000109	0·102	0·102	730
	83	0·086	0·000117	0·128	0·127	980
2,760	0	0·108	0·000094	0·067	0·067	1,230
	17	0·133	0·000093	0·082	0·082	1,510
	36	0·165	0·000102	0·094	0·094	1,870
	54	0·163	0·000100	0·094	0·094	1,850
	83	0·214	0·000106	0·117	0·116	2,430
4,600	0	0·196	0·000093	0·073	0·073	2,230
	17	0·204	0·000095	0·074	0·074	2,320
	37	0·261	0·000099	0·091	0·091	2,960
	54	0·257	0·000098	0·091	0·091	2,920
	83	0·313	0·000105	0·103	0·103	3,560

IX. SLATE.

We have also tested a few dielectrics of normal and abnormal dielectric constant such as slate and sulphur, which are not used for cable or condenser dielectrics, but which have a special interest.

We obtained some thin slate of good quality and built up with it a plate condenser. The slate was first most carefully dried by baking it for several days in an electric oven. The ratio of total coated surface to thickness of the slate was 88.

The slate condenser was tested as usual on our capacity bridge, and the condensed results are embodied in Table XXV. and delineated in

Figs. 33 and 34 for the three frequencies and for various temperatures.

It will be seen that the conductance increases with temperature and with frequency, and that the ratio S/Cp and the power factor

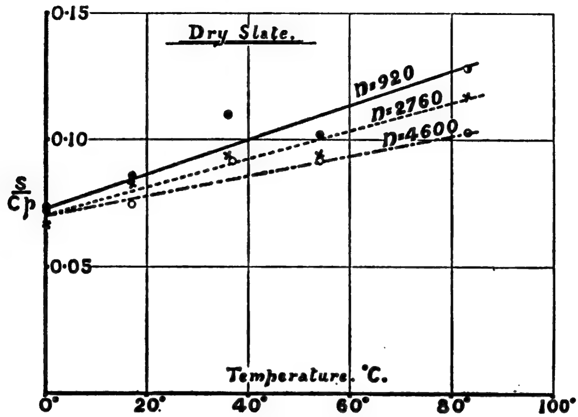


FIG. 33.—Variation of $\frac{S}{Cp}$ with Temperature and Frequency for Slate Condenser.

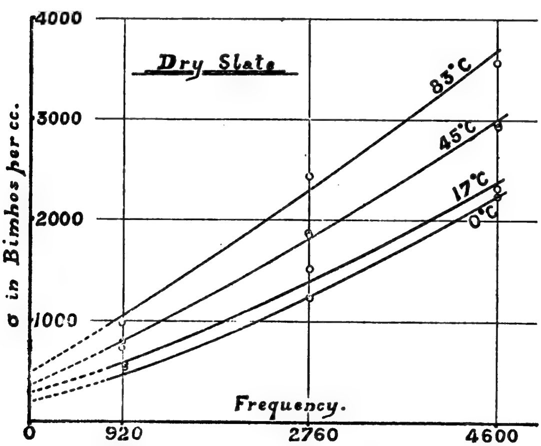


FIG. 34.—Variation of Conductivity with Temperature and Frequency for Slate.

increase with temperature and generally decrease with frequency The capacity readings are a little irregular.

These irregularities are no doubt due to imperfect desiccation. If the slate is imperfectly dried or not dried at all, we obtained the measurements shown in Tables XXVI. and XXVII.

TABLE XXVI.

Dielectric: Slate (partially dried).
Approximate Dimensions: Area = 18·3 sq. cm.
Thickness = 0·21 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 88.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	19	0·21	0·000156	0·232	0·226	2,400
	40	0·24	0·000155	0·264	0·255	2,700
	59	0·12	0·000123	0·172	0·169	1,400
	82	0·09	0·000115	0·126	0·125	1,000
2,760	19	0·43	0·000131	0·191	0·187	4,900
	41	0·51	0·000132	0·223	0·217	5,800
	59	0·28	0·000116	0·137	0·136	3,200
	82	0·21	0·000106	0·113	0·112	2,400
4,600	19	0·59	0·000122	0·166	0·164	6,700
	42	0·75	0·000127	0·206	0·202	8,500
	59	0·43	0·000110	0·136	0·135	4,900
	83	0·33	0·000102	0·113	0·112	3,800

TABLE XXVII.

Dielectric: Slate (not dried).
Approximate Dimensions: Area = 18·3 sq. cm.
Thickness = 0·21 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 88.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	15	0·26	0·000359	0·124	0·123	3,000
	42	0·29	0·000172	0·291	0·280	3,300
	63	0·30	0·000173	0·299	0·287	3,400
2,760	15	1·27	0·000322	0·228	0·222	14,400
	42	0·64	0·000146	0·252	0·244	7,300
	63	0·56	0·000141	0·230	0·224	6,400
4,600	15	2·56	0·000298	0·298	0·286	29,100
	42	0·85	0·000139	0·213	0·208	9,700
	63	0·80	0·000132	0·210	0·206	9,100

In the case of the undried slate the power factor for corresponding temperatures and frequencies is almost always greater or much greater than for the well-dried slate. Hence moisture is a determining cause.

The observed values of the conductance only agree approximately with a formula of the type $A + B\,n$, or at least only in the case of the observations made at 36° C. and 54° C. The dielectric constant obtained from the capacity value at 17° C. and 920 p.p.s. is 12·8, which is fairly in accordance with other determinations which have been made of dielectric constants for sedimentary rocks.

TABLE XXVIII.

Dielectric: Sulphur.
Approximate Dimensions: Area = 800 sq. cm.
Thickness = 0·54 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}480.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	16	0·001	0·000548	0·0003	0·0003	0·7
	40	0·000	0·000545	0·0001	0·0001	0·0
	62	0·001	0·000546	0·0002	0·0002	0·7
2,760	16	0·004	0·000548	0·0004	0·0004	2·7
	40	0·001	0·000546	0·0001	0·0001	0·7
	62	0·003	0·000547	0·0002	0·0002	2·0
4,600	16	0·005	0·000548	0·0003	0·0003	3·4
	40	0·000	0·000546	0·0000	0·0000	0·0
	62	0·000	0·000548	0·0000	0·0000	0·0

X. SULPHUR.

We thought it would be interesting to test some pure elementary solid dielectric, and selected therefore sulphur as the best example. A metal mould was constructed in which we could cast some slabs of sulphur, each about 12 × 12 cm. in side and 0·54 cm. thick. The slabs were very smooth and uniform. Ten such slabs were made up with sheets of tinfoil 10 × 10 cm. into a condenser, with two guard-plates on either side, the whole being tightly bound together with silk ribbon. The total sectional area was 800 sq. cm., and the dimension ratio

(area/thickness) was 1,480. This condenser was tested on the capacity bridge at three temperatures and three frequencies, and the compressed results are embodied in Table XXVIII.

It will be seen that the capacity hardly varies with either temperature or frequency over the ranges employed. Also that the ratio $S/C\,p$ is vanishingly small and the conductance also.

The value of the capacity at 16° C. and 920 p.p.s. indicates a dielectric constant of 4·2. This is quite in agreement with values found by other observers. The conductivity measurements indicate an extremely high specific conductivity for alternating currents, which is quite in agreement with the known very high insulating power of sulphur for steady or direct currents.

Summary.

It will be convenient, then, to summarise the results of this research and to draw some conclusions.

We therefore collect into two Tables XXIX. and XXX. the results for the various dielectrics tested. Owing to the large number of figures of observation we shall only take those values which refer to observations made at normal atmospheric temperature. For the three frequencies used we have calculated by formula (36) and (37) the approximate dielectric constant and resistivity in megohms per centimetre cube of the various dielectrics.

It will be seen that the alternating-current dielectric constants of the crown glass, celluloid, dry Manilla paper, paraffin, ebonite, and mica are quite of the same order as the values obtained with steady electric force. On the other hand the values for indiarubber, pure and vulcanised, and for gutta-percha are rather lower than the values obtained with unidirectional electric force.

The general agreement of the dielectric constants obtained by our method for alternating electric force of telephonic frequency with the values obtained by other methods is a fair proof that the measurements made by us are substantially accurate. It must be remembered, however, that with soft dielectrics, such as indiarubber, it is very difficult to be certain of the precise thickness, and also of the real effective cross-section of the dielectric. The figures in Table XXIX. bring out, however, certain interesting results. They show, for instance, that gutta-percha has an abnormally low alternating-current dielectric resistivity, or large conductivity, and that it has abnormally large values for the ratio S/C when compared with vulcanised indiarubber. The power factor of vulcanised indiarubber at ordinary temperatures is only $\frac{1}{10}$ of that of gutta-percha, and its alternating-current resistivity is 10 times as great, and therefore its ratio S/C is 10 times smaller at ordinary temperatures, say 16–20° C. These measurements show also that the value obtained for the so-called dielectric resistance of insulators by measuring the current which flows through them after applying for 1 minute a steady voltage has very little relation to the

true alternating-current resistivity, with which alone we are concerned in telephony.

This latter number, as obtained and measured by us, is the real index of the energy dissipation in the dielectric. For the total alternating-current resistivity reckoned in megohms is the number which must be divided into the square of the potential difference of the two conducting surfaces of the cable or condenser to obtain the power absorption in microwatts. The so-called dielectric resistance of such bodies as glass, ebonite, gutta-percha, as measured after 1 minute's electrification in the usual way with a steady voltage, is a number reckoned in thousands or millions of megohms.

Thus the handbooks give as the dielectric resistance of gutta-percha as used on cables $3{\cdot}5 \times 10^8$ megohms per centimetre cube at 75° F., and for pure indiarubber 18×10^9 megohms per centimetre cube at 15° C., both after 1 minute's electrification. But these numbers are nearly 100,000 times greater than the true alternating-current resistivity for the telephonic standard frequency of 800 p.p.s.

In the same manner the direct-current dielectric constant of indiarubber is given in the books as varying between 3·0 and 5·5, and that of gutta-percha from 3·5 to 7·0 when tests are made with indiarubber-insulated or gutta-percha-insulated cables. These direct-current values are, however, quite inapplicable in telephonic calculations. In these latter the true values are those as obtained by us.

In Table XXX. we have collected certain data from the previous tables and calculated for each dielectric the value of the specific conductance per centimetre cube (σ) in bi-mhos ($= 10^{-12}$ mho) for normal temperatures, and it will be seen that it can be expressed in the form $\sigma = a + b\,n$, where a and b are constants and n is the frequency. For all dry and anhydrous bodies the term a is zero. For glass, celluloid, undried paper, and for gutta-percha it has a varying large value, whilst in the case of gutta-percha this term is negative.

This does not imply that the direct-current conductivity for gutta-percha is negative, which would be meaningless, but only that the conductivity line for 19° C. from which the equation is deduced is concave upwards, as shown in the diagram in Fig. 30, and therefore that the upper part of the line which is nearly straight, would, if produced backwards, have a negative intercept.

[Since sending in this paper we have tested certain of the dielectrics, viz., vulcanised indiarubber, gutta-percha, and celluloid in carbonic-acid snow, and found clear indications that the power factor and alternating-current conductivity of these bodies has a maximum value for certain particular temperatures, which in the case of gutta-percha is + 10° C., for vulcanised indiarubber is — 30° C., and for celluloid still lower. See Appendix.]

TABLE XXIX.

Dielectric.	Frequency n.	Approximate Dielectric Constant k for Alternating Electric Force of Frequency n.	Approximate Percentage Variation of k per Degree Centigrade.	Approximate Alternating Current Resistivity in Megohms per Centimetre Cube for Frequency n.	Power Factor for Frequency n.	Ratio $\frac{S}{C} = s$.	Remarks.
Glass at 17° C. ...	920	6·60	+ 0·260	16,900	0·018	104·0	
	2,760	6·50	+ 0·190	6,400	0·016	277·0	
	4,600	6·50	+ 0·160	4,000	0·015	433·0	
Celluloid at 15° C. ...	920	4·02	+ 0·523	28,000	0·012	66·0	
	2,760	4·00	+ 0·440	16,000	0·012	179·0	
	4,600	4·00	+ 0·384	11,500	0·012	363·0	
Dry Manilla paper at 19° C.	920	1·95	+ 0·108	140,000	0·007	41·6	
	2,760	1·95	+ 0·106	46,700	0·007	125·0	
	4,600	1·95	+ 0·112	26,000	0·008	225·0	
Paraffin wax at 17° C.	920	2·36	Nearly zero	2,460,000	0·0003	2·0	
	2,760	2·36	"	493,000	0·0005	10·0	
	4,600	2·36	"	296,000	0·0005	17·0	
Mica at 16° C. ...	920	4·00	+ 0·060	423,500	0·001	7·0	
	2,760	4·00	+ 0·060	141,200	0·001	21·0	
	4,600	4·00	+ 0·060	50,000	0·002	58·0	

Ebonite at 19° C. ...	920	3·17	+ 0·360	148,500	0·005	24·0	
	2,760	3·15	+ 0·310	38,500	0·005	93·0	
	4,600	3·14	+ 0·290	23,100	0·005	155·0	
Pure indiarubber at 18° C.	920	2·60	− 0·062	145,500	0·005	30·0	The temperature coefficient of the dielectric constant appears to be negative for indiarubber at ordinary temperatures.
	2,76	2·60	− 0·062	54,500	0·005	80·0	
	4,600	2·60	− 0·062	35,400	0·004	123·0	
Vulcanised indiarubber at 17° C. ...	920	2·73	− 0·150	343,300	0·002	12·0	
	2,760	2·71	− 0·130	103,000	0·002	40·0	
	4,600	2·71	− 0·140	38,100	0·004	108·0	
Gutta-percha at 15° C.	920	2·86	+ 0·105	33,700	0·020	117·0	
	2,760	2·86	+ 0·124	10,200	0·023	389·0	
	4,600	2·86	+ 0·133	5,600	0·025	708·0	
Dry slate at 17° C. ...	920	12·70	Very small, but not determinate	1,760	0·086	500·0	
	2,760	11·90		660	0·082	1,430·0	
	4,600	11·90		430	0·074	2,147·0	
Sulphur at 16° C. ...	920	4·20	Very small	1,480,000	0·0003	2·0	
	2,760	4·20		370,000	0·0004	8·0	
	4,600	4·20		300,000	0·0003	10·0	

TABLE XXX.

Dielectric.	Centigrade Temperature. = T.	Frequency. = n.	Approximate Dimension Ratio of the Condenser. = A/t.	Conductance in Micromhos. = S.	Approximate Specific Conductance per Centimetre Cube in Micro-micromhos. = $\sigma = a + bn$.
	°C.				
Crown glass...	17	920 2,760 4,600	2,670	0·158 0·417 0·657	$S = 0{\cdot}023 + 0{\cdot}00014\,n$ $\sigma = 8{\cdot}61 + 0{\cdot}0524\,n$
Celluloid	15	920 2,760 4,600	3,900	0·092 0·246 0·499	$S = 0{\cdot}015 + 0{\cdot}000084\,n$ $\sigma = 3 + 0{\cdot}022\,n$
Dry Manilla paper	19	920 2,760 4,600	3,500	0·025 0·075 0·135	$S = 0 + 0{\cdot}000027\,n$ $\sigma = 0 + 0{\cdot}0077\,n$
Undried Manilla paper	18	920 2,760 4,600	3,500	0·373 0·675 0·916	$S = 0{\cdot}265 + 0{\cdot}00014\,n$ $\sigma = 75{\cdot}7 + 0{\cdot}04\,n$
Dry Manilla paper, paraffined ...	17	920 2,760 4,600	6,900	0·091 0·282 0·459	$S = 0 + 0{\cdot}0001\,n$ $\sigma = 0 + 0{\cdot}0143\,n$
Undried Manilla paper, paraffined	19	920 2,760 4,600	2,270	0·230 0·454 0·639	$S = 0{\cdot}14 + 0{\cdot}00011\,n$ $\sigma = 61{\cdot}6 + 0{\cdot}048\,n$

Dry-core paper cable	19	920 2,760 4,600	—	0·018 0·057 0·104	$S = 0 + 0·001173\,n$
Mica	17	920 2,760 4,600	7,200	0·017 0·053 0·144	$S = 0 + 0·00002\,n$ $\sigma = 0 + 0·002\,n$
Ebonite	19	920 2,760 4,600	1,040	0·007 0·027 0·045	$S = 0 + 0·00001\,n$ $\sigma = 0 + 0·01\,n$
Pure Para indiarubber	18	920 2,760 4,600	1,310	0·009 0·024 0·037	$S = 0·002 + 0·0000076\,n$ $\sigma = 1·53 + 0·0058\,n$
Vulcanised indiarubber	17	920 2,760 4,600	1,030	0·003 0·010 0·027	$S = 0·002 + \frac{118}{10^{14}}\,n^2$ $\sigma = 2·0 + \frac{1180}{10^{12}}\,n^2$
Vulcanised indiarubber	41	920 2,760 4,600	1,030	0·008 0·019 0·025	$S = 0·003 + 0·0000055\,n$ $\sigma = 2·9 + 0·0053\,n$
Gutta-percha	19	920 2,760 4,600	945	0·019 0·082 0·154	$S = -0·016 + 0·000038\,n$ $\sigma = -16·9 + 0·04\,n$
Gutta-percha	27	920 2,760 4,600	945	0·009 0·043 0·092	$S = -0·009 + 0·00002\,n$ $\sigma = -9·52 + 0·0216\,n$

Conclusions.

The following are the conclusions arrived at as a result of the measurements above described:—

1. All the dielectrics so far tested prove to possess a true dielectric conductivity for alternating currents considerably greater than for steady unidirectional currents.

2. This increased conductivity implies greater power dissipation for the same terminal potential difference or voltage.

3. The alternating-current conductivity increases with the temperature except in the case of vulcanised indiarubber between -30° and $+20$ C°., and gutta-percha above 10° C., and celluloid between -50° C. and 0° C., in all of which cases it decreases with rise of temperature. In the case of mica and very dry paper it is not affected to any sensible extent by rise of temperature over a range between 0° C. and 60° C.

4. The alternating-current conductivity is in most cases a linear function of the frequency and may be expressed in the form $\sigma = a + b\,n$, where a and b are coefficients, which are functions of the temperature, and n is the frequency.

5. The alternating-current conductivity, especially that part of it denoted by a, is greatly increased by the presence of moisture in the dielectric. This part is probably identical with the true direct-current conductivity.

6. The part of the conductivity denoted by the coefficient a is possibly electrolytic in nature, whilst the part proportional to the frequency is a consequence of an energy loss which is possibly analogous to the hysteresis loss in iron.

7. The dielectric constant for alternating electric force is in most dielectrics rather smaller than that for steady or unidirectional electric force. In no case is it larger.

8. In the case of pure indiarubber and vulcanised indiarubber the temperature coefficient of the dielectric constant may perhaps be negative within the range of telephonic frequencies, and 0° C. to 50° C., but this result is not quite certain.

9. The ratio $S/C\,p$, nearly identical with the power factor, is, for some dielectrics such as mica and dry paper, a constant independent of frequency and temperature. For most dielectrics it increases with rise of temperature but decreases with rise of frequency. The power-factor variation with temperature of vulcanised indiarubber and gutta-percha is quite abnormal.

10. Those dielectrics such as celluloid and gutta-percha, which have large alternating-current conductivity, although free as far as possible from moisture, also exhibit in a marked manner the phenomena of dielectric absorption and residual charge.

11. For certain dielectrics there is a temperature at which the power factor and alternating conductivity have maximum values.

See Appendix for details of the observations.

APPENDIX.

Since this paper was communicated to the Institution we have carried out a series of measurements with the gutta-percha, vulcanised indiarubber, and celluloid condensers over a wide range of temperature lying between the temperature of liquid air $-185°$ C. and some temperature between 50° C. and 100° C. By the use of liquid air or of solid carbonic dioxide dissolved in ether we prepared baths in Dewar vacuum vessels in which the condensers could be immersed, calibrated thermo-junctions of copper and eureka being employed to determine the temperature of the dielectrics of these condensers.

The condensers were cast into blocks of paraffin wax, so that when

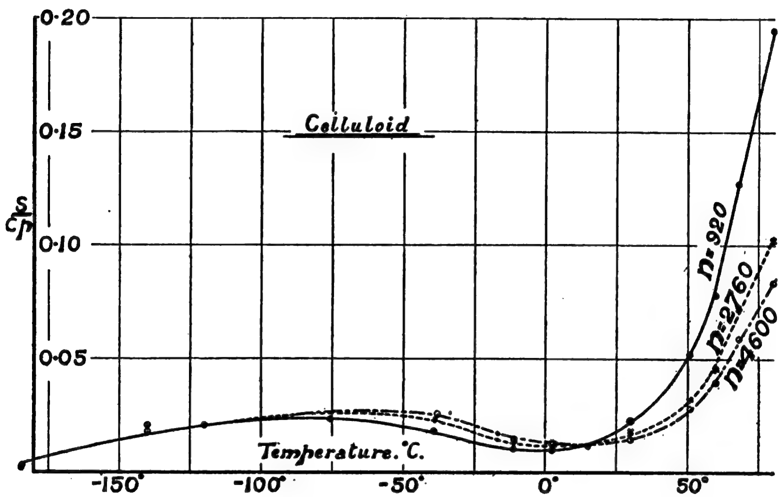


FIG. 35.—Variation of $\frac{S}{Cp}$ (Power Factor) with Temperature and Frequency for Celluloid Condenser, over a wide range of Temperature $-185°$ C. to $+75°$ C.

cooled in the refrigerant and raised up subsequently into the upper part of the vacuum vessel, the gradual heating up of the dielectric proceeded sufficiently slowly to enable measurements on our capacity bridge to be taken for various known temperatures and the three frequencies. The results for the celluloid, vulcanised indiarubber, and gutta-percha condensers are tabulated in Tables XXXI., XXXII., and XXXIII., and the variation of the power factor with temperature and frequency is shown for each case by the curves in Figs. 35, 36, and 37.

Celluloid.—The capacity, power factor, and conductivity for various temperatures between $-185°$ C. and $+75°$ C. are given in Table XXXI.

As regards dielectric constant, it will be seen from the capacity measurements given in the fourth column, when reduced by the aid of formula (36), that the dielectric constant of celluloid falls to nearly 2·0 at — 184° C. and is about 3·0 at — 75° C., whereas it is 4·0 at 0° C. and 6·0 at 100° C.

TABLE XXXI.

Dielectric: Celluloid.
Electrodes: Tinfoil.
Approximate Dimensions: Area = 57 sq. cm.
Thickness = 0·0146 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 3{,}900.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	—184	0·011	0·000688	0·0028	0·0028	2·9
	—140	0·098	0·000830	0·0204	0·0204	25·1
	—120	0·102	0·000868	0·0203	0·0203	26·1
	— 75	0·138	0·001019	0·0234	0·0234	35·3
	— 39	0·126	0·001174	0·0186	0·0186	32·4
	— 11	0·084	0·001414	0·0103	0·0103	21·6
	2·5	0·083	0·001480	0·0097	0·0097	21·3
2,760	—184	0·029	0·000688	0·0024	0·0024	7·3
	—140	0·251	0·000822	0·0176	0·0176	64·3
	—120	0·292	0·000848	0·0199	0·0199	75·0
	— 75	0·409	0·000997	0·0237	0·0237	105·0
	— 38	0·476	0·001155	0·0238	0·0238	122·0
	— 11	0·332	0·001409	0·0136	0·0136	85·0
	2·5	0·293	0·001447	0·0117	0·0117	75·1
4,600	—184	0·044	0·000688	0·0022	0·0022	11·2
	—140	0·410	0·000812	0·0175	0·0175	105·0
	—120	0·511	0·000838	0·0211	0·0211	131·0
	— 75	0·671	0·000989	0·0235	0·0235	172·0
	— 38	0·858	0·001149	0·0259	0.0259	220·0
	— 11	0·601	0·001399	0·0149	0·0149	154·0
	2·5	0·534	0·001442	0·0128	0·0128	137·0

Hence there is an immense reduction in the dielectric constant on cooling to the temperature of liquid air. There is also a large reduction in the temperature coefficient of the dielectric constant with temperature, but there is very little change either in the value of the dielectric constant or in the temperature coefficient of it with change in frequency. The temperature coefficient is about 0·005 in the neighbourhood of 0° C. and about 0·0033 near — 185° C.

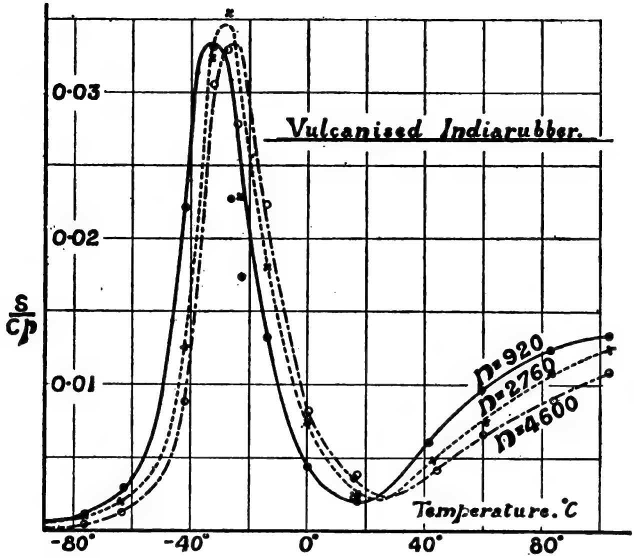


FIG. 36.—Variation of $\frac{S}{Cp}$ (Power Factor) with Temperature and Frequency for Vulcanised Indiarubber over a wide range of Temperature $-90°$ C. to $+100°$ C.

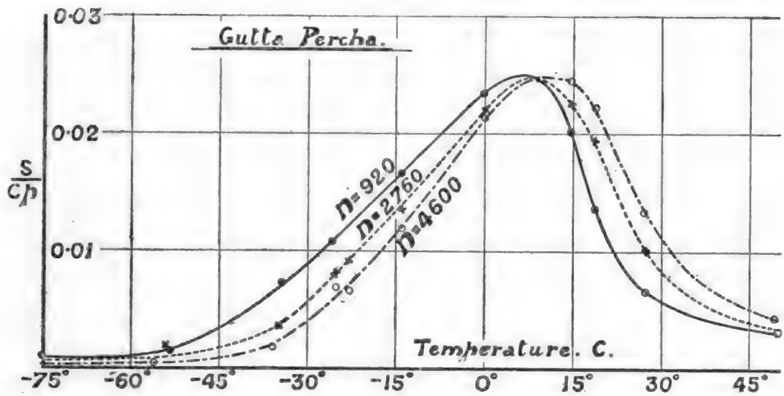


FIG. 37.—Variation of $\frac{S}{Cp}$ (Power Factor) with Temperature and Frequency for Gutta-percha over a wide range of Temperature $-75°$ C. to $+50°$ C.

The conductivity (σ) undergoes curious variations. From 75° C. downwards it decreases steadily until it reaches a minimum value near 0° C. Then it increases again and reaches a subsidiary maximum between — 50° C. and — 75° C. Then it decreases with further cooling

TABLE XXXII.

Dielectric: Vulcanised Indiarubber.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0534 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 1{,}030.$$

Frequency n.	Centigrade Temperature T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	—184	—	0·000221	Very	small	—
	— 76	0·002	0·000253	0·0010	0·0010	2
	— 63	0·004	0·000253	0·0030	0·0030	4
	— 42	0·033	0·000255	0·0220	0·0220	32
	— 32	0·051	0·000266	0·0330	0·0330	50
	— 23	0·027	0·000272	0·0170	0·0170	26
	103	0·019	0·000247	0·0130	0·0130	18
2,760	—184	—	0·000221	Very	small	—
	— 76	0·004	0·000253	0·0009	0·0009	4
	— 63	0·008	0·000253	0·0020	0·0020	8
	— 42	0·055	0·000251	0·0130	0·0130	53
	— 33	0·145	0·000260	0·0320	0·0320	141
	— 23	0·105	0·000267	0·0230	0·0230	102
	103	0·053	0·000246	0·0120	0·0120	51
4,600	—184	—	0·000224	Very	small	—
	— 76	0·003	0·000254	0·0004	0·0004	3
	— 63	0·009	0·000254	0·0010	0·0010	9
	— 42	0·064	0·000251	0·0090	0·0090	62
	— 32	0·227	0·000258	0·0310	0·0310	220
	— 24	0·211	0·000263	0·0280	0·0280	205
	103	0·077	0·000245	0·0110	0·0110	75

and becomes very small at — 185° C. for all frequencies. The conductivity is nearly proportional to the frequency at low temperatures.

Thus at — 75° C. we have $\sigma = b\,n$ where $b = 0{\cdot}038$, whereas at — 140° C. we have $b = 0{\cdot}022$.

The a term remains therefore very small at low temperatures, but there is a certain irregular variation in the value of b with temperature. The variation of conductivity follows generally the same course as the

variation of power factor with temperature, hence b has a subsidiary maximum about $-75°$ C.

Vulcanised Indiarubber.—The observations over a range of temperature from $-184°$ C. to $+100°$ C. are given in Table XXXII. and the value of the power factor for various temperatures plotted in Fig. 36. It will be seen that the variation of power factor with temperature is most extraordinary. The power factor falls regularly with temperature to some point near 20° C., and then rises with great rapidity again until

TABLE XXXIII.

Dielectric: Gutta-percha.
Approximate Dimensions: Area = 55 sq. cm.
Thickness = 0·0582 cm.

$$\frac{\text{Area}}{\text{Thickness}} = 945.$$

Frequency n.	Centigrade Temperature. T.	Conductance in Micromhos S.	Capacity in Microfarads C.	$\frac{S}{Cp}$	Power Factor.	Conductance in Bi-mhos per Centimetre Cube σ.
920	−184	—	0·000183	Very	small	—
	− 75	0·001	0·000223	0·001	0·001	1
	− 53	0·002	0·000223	0·002	0·002	2
	− 34	0·009	0·000221	0·007	0·007	10
	− 26	0·015	0·000231	0·011	0·011	15
2,760	−184	—	0·000184	<0·002	<0·002	—
	− 75	0·003	0·000224	0·001	0·001	3
	− 54	0·008	0·000224	0·002	0·002	9
	− 35	0·013	0·000222	0·003	0·003	14
	− 25	0·033	0·000228	0·008	0·008	35
4,600	−184	—	0·000182	<0·001	<0·001	—
	− 75	—	0·000223	<0·001	<0·001	—
	− 56	0·003	0·000223	0·001	0·001	3
	− 36	0·012	0·000223	0·002	0·002	13
	− 25	0·046	0·000227	0·007	0·007	49

at some point near $-30°$ C. it attains a maximum value which is nearly 14 times its minimum value at $+20°$ C. It then falls again and becomes exceedingly small at $-80°$ and vanishingly small at $-185°$ C.

It will be seen, however, that the variation in capacity and therefore in dielectric constant is very small. It has, however, a maximum value at about $-23°$ C., for all frequencies at this temperature its value is near 3·0, but at higher and lower temperatures the value is is rather less, being 2·4 at $-184°$ C. and 2·7 at $+103°$ C.

As regards conductivity, it will be noted that for the same frequency it has a maximum value in all cases near $-32°$ C. For the same temperature the conductivity is, however, not a linear function of the frequency except in the case of $-32°$ C. in which the conductivity is nearly expressed by the linear function $\sigma = 5 + 0{\cdot}05\, n$. The coefficient a is in all cases very small. The variation of conductivity with temperature at the same frequency follows the same general course as the power factor. Starting from 100° C. and lowering the temperature, we find that the conductivity first decreases to a minimum near 17° C. and then rises to a maximum near $-32°$ C. and then falls again continuously as the temperature is still farther lowered.

Gutta-percha.—We have taken the same observations for the gutta-percha condenser cooled down to the temperature of liquid air. The results are embodied in Table XXXIII. and the variation of power factor with temperature is shown by the curves in Fig. 37. Below $-75°$ C. the only change is a still further reduction of power factor and conductivity. It will be seen on comparing Fig. 29 with Fig. 37, that the result of cooling below 0° C. is not to introduce any abnormality.

The conductivity continues to decrease steadily as the temperature is lowered. In these three cases, viz., celluloid, vulcanised indiarubber, and gutta-percha, there is evidence that as the temperature is lowered towards the absolute zero the dielectric conductivity continues to be reduced towards zero. Hence it is possible that at the absolute zero all good dielectrics have zero conductivity; just as all pure metals have zero resistance. This difference offers a wide field for research in ascertaining the behaviour of intermediate bodies, which we hope at some future time to undertake.

Discussion.

Dr. Russell. Dr. Alexander Russell: This paper marks the beginning of a new chapter of electrical theory, and I shall be surprised if important practical results do not rapidly follow. The experimental results prove that the effective conductance of dielectrics is a linear function of the frequency. This will necessitate putting some of the ordinary theory of the transmission of telephone currents back into the melting-pot; but this is all to the good, as it has long been recognised that the assumption of constant conductivity in dielectrics leads in many cases to erroneous results. The first formula the authors quote, for instance, is obtained on the assumption of constant conductivity of the dielectric, and is supposed to fix a superior limit to the possible values of the attenuation constant. We now see that this so-called constant varies enormously with the frequency, and we know that it varies largely with temperature. We can hardly, therefore, continue to call it a constant. For a similar reason, following Carey Foster, I have for a long time called the dielectric constant the dielectric coefficient. I have often heard mathematicians express astonishment at the loose way engineers

Dr. Russell.

use the word constant. The everyday test for the insulation resistance of cables is criticised by Dr. Fleming. The quantity found ought not to be called insulation resistance, but although the number obtained is labelled unscientifically, the test has proved of great practical use for weeding out bad cables. For measuring the properties of the insulating covering, however, a better test might now be devised. I think that Dr. Fleming's instructive model of an absorptive condenser shown in Fig. 2 might be improved by putting a non-inductive resistance in parallel with the two condenser circuits. The growth of the main current in such a system is very similar to that in an absorptive condenser. The method described of getting pure sine-shaped currents is very simple, and ought to prove useful in many cases. The fact that the calculated theoretical minimum current agrees with the observed current is, in my opinion, quite a rigorous proof that the resonator has selected the desired harmonic. I prefer the general word "resonator" to the word "filter," as the latter word gives a misleading idea of what happens. Hence the phrase, "resonating the harmonics" is better than "filtering the harmonics." In order to make approximate measurements of the properties of dielectrics the authors make the fundamental assumption that every condenser can be represented by a perfect capacity C shunted by a resistance R. The authors find that this assumption is permissible, provided that the conductance $1/R$ varies with the frequency according to a linear law, and that the capacity C in general slightly diminishes as the frequency increases, although in some cases it is practically constant. If this assumption were rigorously true there would be no absorption, and a new explanation would have to be found for the curious effects produced by the rapid discharge of condensers through low-resistance galvanometers. A study of this latter phenomena makes it almost certain that any accurate model of a condenser must have resistance in series with capacity as well as shunting it. Let us suppose, then, that we can represent the actual condenser by a resistance r in series with a theoretically perfect condenser C, both being shunted by a resistance R. We thus introduce a new quantity r, and this naturally enables us to represent the actual condenser phenomena more accurately. The above model of a condenser would show, for instance, residual charge, and would reproduce the phenomena connected with rapid discharges. It can be readily shown to be equivalent to a capacity C_1 shunted by a resistance R_1, provided that—

$$C_1 = \frac{C}{1 + p^2 C^2 r^2}, \text{ and } \frac{1}{R_1} = \frac{1}{R} + \frac{p^2 C^2 r}{1 + p^2 C^2 r^2}.$$

We see, then, that as the frequency $p/2\pi$ increases, C_1 should in certain cases diminish, and the apparent conductance $1/R_1$ should increase, just as the authors found. To make it fit more exactly with their experiments, we would have to suppose that $1/r$ varied as the frequency. In addition, we see that as r increases, the frequency remaining constant, the latter term attains a maximum value when $1/r = pC$. Hence

Dr. Russell. an explanation might be given in this way of why it is that the alternating conductivity of certain dielectrics attains a maximum value as the temperature increases. In my opinion the main utility of the authors' results lies in the fact that we can now attempt to take into account in our working theories the variation of leakance with frequency. It would have needed no small amount of courage to have attempted this before the publication of this paper. In conclusion, I must say a word in appreciation of the authors' variable capacity bridge. It is simple, cheap, and accurate. Since the arms of the bridge also are air condensers, the losses in them are negligible, and hence the bridge is excellently adapted for studying the properties of dielectrics.

Mr. Cohen. Mr. B. S. COHEN: The authors have dealt in their paper with matters of considerable importance to telephone and telegraph engineers. I would draw particular attention to the third paragraph on page 326. In spite of the work that has been done in alternating-current measurements it is astonishing that even now the importance of the alternating-current constants of telephonic and telegraphic lines and apparatus is not fully realised, and this is the more inexcusable as it is possible nowadays to obtain apparatus by which these measurements can be made with, if anything, greater ease than the corresponding direct-current measurements. For telephonic work the behaviour of apparatus over a certain range of frequency and current amplitude is required, and the range, both of frequency and amplitude, is fairly well ascertained, and to obtain all the data necessary to study the telephonic behaviour of a dielectric, it is certainly advisable to have curves for its dielectric constant and conductance over the telephonic range, both for current and frequency. Many measurements have been made in the last few years with telephone condensers using a bridge method somewhat similar to the Wien type shown in Fig. 7 of this paper, and some curious results have been obtained; for example, condensers sold as possessing a capacity of 2 microfarads and measuring somewhere about that figure by the direct-current method, have been found to possess a capacity falling as low as 0·6 microfarad when measured with telephonic current. Again, no paraffined paper telephone condenser has been found to have an effective insulation higher than about 16,000 ohms, and many condensers with direct-current insulation of the order of hundreds of megohms possess effective insulations as low as 1,500 ohms. These figures indicate that considerable energy losses occur when using such condensers on telephonic circuits, and transmission tests confirm this indication. For some years it has been the practice to specify that telephone condensers shall possess their indicated capacity both for direct current and telephonic current. On page 339, fourth line below Fig. 4, is not the word "selected" a mistake for "rejected"? Has Dr. Fleming considered the possibility of using the wave filter due to G. A. Campbell, but inverted, so as to wipe out all frequencies below a certain value in order to obtain his higher harmonics? The Campbell filter is an arrangement of capacities in bridge and inductances in series, and

thus arranged will wipe out all frequencies above a certain value, and if the capacities are put in series and the inductances in bridge, it would appear that this arrangement would wipe out all frequencies below a certain value. The method adopted for testing the purity of the wave-form for the Crompton alternator by measuring its current through and potential across a known condenser is an extremely good one, and has always been used at Telephone House for this purpose. **Mr. Cohen.**

Turning now to cable dielectrics and, particularly, dry paper, the authors have made some extremely interesting and valuable measurements. In the table given on page 376, the authors show that the effective insulations with telephonic currents for dry-core paper cable is of the order of a megohm per mile loop, and this result has also been obtained by measurements carried out at Telephone House by a bridge method of the Wien type. The latest measurements using a bridge method as carried out by the American Telegraph and Telephone Company give also values of the same order, as do also some comparatively recent measurements of Dr. Ebeling. Other measurements made by Dr. Breisig and by Mr. Bela Gati and some results obtained by Mr. Shepherd and myself,* all using vector methods of measurement, give effective insulations much lower than this (of the order of a ¼ megohm or less per mile loop). Although the angles to be measured are in some cases very small and a considerable likelihood of error is thus introduced, the difference between the vector and bridge methods of measurement could scarcely be accounted for by this. Perhaps the authors can suggest some further explanation.

Major O'Meara. Major W. A. J. O'MEARA: It is a matter of great satisfaction to me that a remark I made in the paper which I read here in December, 1910,† should have caused Dr. Fleming and his colleague to devote their attention to the subject of the properties of dielectrics, and we are fortunate in having the results of their investigations placed before us in the paper that we have listened to to-night. This paper has brought to our notice in a very complete form much matter concerning which we have had information of an uncertain kind only in the past. For instance, in connection with paper it has been known that damp did somewhat seriously affect the property of the paper used in the insulation of the conductors of cables, but I have never realised how very important a bearing this question of dryness of the paper had on the value of the power factor. I believe this is the only country in which in connection with the distribution system of telephone networks any provision has been made for the desiccation of the cables. There is, so far as I know, no other country in which similar provision has been made. I have discussed the matter of making provision for desiccating cables with Continental engineers and others, but they have not considered the subject to be one of very great importance. Now, however, we have in Tables VII. and VIII. figures which enable us to make useful comparisons, and we see that at about the same temperature, that is 18° for

* *Proceedings of the Institution of Electrical Engineers*, vol. 39, p. 503, 907.
† Ibid., vol. 46, p. 309, 1911.

Major O'Meara.

the damp paper and 19° for the dry paper, the value of $\frac{S}{C}$ in the one case is ten times that in the other case. Therefore this information gives an increased value to our desiccating plant. Another matter of importance which Dr. Fleming has drawn attention to is the question of the design of submarine cables. As a matter of fact, the importance of the twin-wire system has been understood for some little time past. For instance, in the diagram of cable sections which I gave in the paper that I read here,* I think you will see there are two cases in which it was proposed to place the conductors together in an insulating tube with paper or gutta-percha as a separator between them. I fear the property which paper possesses for absorbing damp makes it very unsuitable for use in connection with submarine cables. However, I think that cable-makers might well turn their attention to vulcanised indiarubber. If that can be used in tape form and wound round the conductors, and if the conductors are then put together in the same way as they are in the case of a lead cable, but with a gutta percha insulating tube taking the place of the lead sheathing, I think we should have a very much more efficient telephone cable than is provided by existing designs of submarine cables.

Mr. Campbell.

Mr. A. Campbell: The authors' results will be of great use to practical men, who will appreciate the thoroughly systematic way in which all have been tabulated and illustrated. There is only one important statement in the paper with which I would express disagreement, and this is a matter concerning the method and not the results of the measurements. On page 347 the authors state that no arrangement such as a buzzer, hummer, or current interrupter of any kind can be substituted for the sine-wave alternator, or for the alternator and wave filter as used. Now as I have for years past used buzzers, hummers, and current interrupters constantly for exactly such tests on small condensers, short lengths of cable, and standard condensers, I can state with confidence that such arrangements (provided they are rightly used) are as good, if not better, than any form of high-frequency alternator, while their initial cost and the trouble of working them are both very much less. As a cheap and simple source of high-frequency current for such tests will be of interest to other observers, I have shown in Fig. A a good way of arranging an electric trumpet or microphone hummer for working a Wien series resistance bridge (for clearness omitting details of the hummer).

The subdivided paraffin paper condenser k is adjusted to give (with the low-resistance inductance coil L and the rest of the circuit) resonance for the fundamental frequency of the hummer. With a battery B of 6 volts driving the hummer, it is possible to get quite considerable voltages (say 100 volts, if desired) on the corners of the bridge. With frequencies from 300 up to 3,000 $\sim$ per second, the wave-form is so pure that a very good balance is obtained on the telephone. If we wish to use one of the harmonics of the hummer,

* *Proceedings of the Institution of Electrical Engineers*, vol. 46, p. 309, 1911.

Mr. Campbell.

the best results are obtained by inserting between the hummer and the rest of the circuit a mutual inductance wave-form sifter such as I have recently described.* By the help of this sifter the fundamental frequency component is entirely suppressed, and, by adjusting k, frequencies corresponding to various harmonics can then be used in the bridge. For example, with an ordinary electric trumpet (costing 5s.), frequencies of 800, 1,600, 2,400, 3,200, and 4,000 per second are readily obtained, and each of these is sufficiently pure to give good readings on the bridge. In order to find, if possible, any case to which the authors' statements could apply, tests were made with small condensers as similar as possible in capacity and variety of materials to those described in the paper, and these all gave satisfactory results. For the arms P and Q, 10,000-ohm coils (and in some cases 1,000-ohm coils) were found better with a

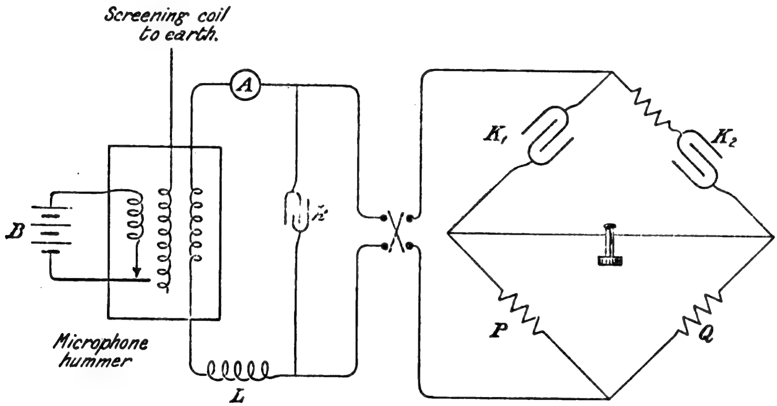


FIG. A.

telephone of 500 ohms resistance than air condensers. It is usually best to work with equal ratio arms; in this case all danger of inequality of inductance or capacity disappears if they are twisted together according to Dr. Heaviside's plan. Microphone hummers are a little more complicated than electric trumpets, but they have the advantage of giving, without any attention, very steady frequencies which can easily be standard values such as 200, 500, 800, 1,000, 2,000 ∿ per second, and so on. I may notice a few more points. The value of the inductive capacity (1·95), found by the authors for dry telephone paper is near the mean (2·0) for a number of samples which I tested at low frequencies.† It must be remembered, however, that the density of such paper varies considerably, and that the inductive capacity depends upon the density. It is interesting to see how Mr. Rayner's

* *Proceedings of the Physical Society*, vol. 24, p. 107, 1912.
† *Proceedings of the Royal Society*, A., vol. 78, p. 196, 1906.

Mr. Campbell.

discovery of the abnormal behaviour of gutta-percha has been extended to lower temperatures and other materials. Referring to page 390, I think that if the hemp had been thoroughly wet the abnormal effect would not have occurred, for a length of gutta-percha cable is found to give practically the same capacity and power factor whether it is immersed in water or mercury. On page 393 some measurements on a gutta-percha covered wire by Mr. Eckersley and myself are quoted. They were only given by us as figures illustrative of the behaviour of such a dielectric, and the gutta-percha tested may have been of quite inferior quality. In fact it is difficult to say what might be defined as "pure gutta-percha," since the material is such a complex mixture, whose qualities also vary considerably with age as it absorbs water. The values given for mica on page 377 cannot really refer to the best mica free from moisture and surface leakage, for good mica condensers give power factors as low as 0·0003.

Mr. Kempe.

Mr. H. R. Kempe: I should like to call attention to the statement made by Professor Fleming, viz., "It is curious that cable manufacturers continue to pay such great attention to the so-called insulation resistance (I.R.) measured by applying a steady or direct-current voltage to the cable and then stating the I.R. as so many megohms per mile after 1 minute's electrification. Except as a rough test of dielectric strength and a means of revealing defects of manufacture the above measurement has very little, if any, scientific value." I totally disagree with that. The whole essence of a test of the kind is to discover defects, and unless the defects can be found before the cable is laid it becomes a very serious matter. There is no question about it but that the well-known system of testing by taking direct continuous-current deflections, which has been in use for over forty years, is one of the very best methods we can have for ascertaining the electrical soundness of a cable. Any method of testing by means of high-frequency alternating currents of small quantity would not answer the required purpose, although it would be useful for supplementing it. In regard to the nature of gutta-percha, it is a fact well known to those who have to deal with submarine cables that the material improves by age. When the cores are first made and turned out "red-hot," as it were, from the gutta-percha press, certain cores may have an insulation of 200 megohms per knot only, but in the course of a few weeks this may run up to 2,000 megohms, or even more. If the insulation instead of going up, goes down, even slightly, then there is in all probability a defect in the core; testing by means of alternating currents of high frequency and low quantity would not show a defect of that kind; it is therefore a system which would be practically useless from a manufacturer's point of view. The authors refer to the effect of moisture upon the insulation value of paper, and reference is made to its effect upon gutta-percha. I think the fact that a slightly higher insulation value was obtained after the sample of gutta-percha had been soaked in water, was not due to any moisture having impregnated the material; gutta-

percha is practically impervious to moisture, and certainly mere soaking in water would not cause the latter to become absorbed; the result was probably due to the treatment to which the gutta-percha was subjected when it was dried. Reference is made to the value of S/C obtained on the Anglo-French telephone cable, namely, 114. I may mention that in the Anglo-Belgian telephone cable manufactured and laid last year by Messrs. Siemens, the value of S/C was brought down as low as 12. I doubt whether it will be possible to go materially below this figure. Reference has been made to the considerable improvement which might be obtained by the use of india-rubber, but the value 12 which has been obtained by Messrs. Siemens is so low that there is very little room for further improvement; it is approaching the zero value, and even if it could be brought down to zero the improvement in speaking value which would result would be barely appreciable. If any improvement is likely to take place in the construction of telephone cables it will not in my opinion be due to any improvement in the dielectric, but in lowering the effective resistance of the loading coils. Mr. Kempe.

Allusion is made to the specific resistance of gutta-percha; it is stated to vary from 3·5 to 7·0. Those figures are ridiculous. I do not wish to cast any aspersions on the authors, because they quote certain text-books, and it is the text-books which are at fault. These books have been copying and recopying results which were obtained many years ago with a few specimens of gutta-percha of unknown quality and age. I have personally tested, within the last forty years, a very large number of cable cores insulated with gutta-percha. I have tested cores which when they were turned out from the press had an insulation resistance of 200 megohms, and which after being kept in water for a year have gone up to as much as 4,000 megohms, and sometimes up to 10,000 megohms. The difference between 200 and 10,000 is very considerable—it is certainly not in the ratio of 3·5 to 7·0—and it shows that a definite value cannot be given to the specific resistance of gutta-percha; this specific resistance depends not only upon the nature of the material but upon its age. I think it would be a great advantage if experimenters would be careful to mention the fact, when they give the results of tests of certain materials, that those results only relate to the particular samples tested, and that they do not necessarily hold good for the material generally. There are two other points to which I should like to refer. In reference to the measurements made by the Wien bridge apparatus, one of my assistants, Mr. C. Hay, has given a very great deal of attention to measurements of the kind. His results are so extremely valuable and important that I hope at some future time he will give us the benefit of his researches. He mentioned to me that when a measurement is made by a zero method in which a telephone is used, it is difficult to tell when absolute silence on the telephone is obtained; the sound gradually diminishes as the point of true balance is approached, and eventually it seems as if the sound has entirely disappeared when this is not actually the case. Mr. Hay

Mr. Kempe. has adopted the very simple device of putting a short-circuit key on the telephone; the result is that if when it is thought that a balance is obtained, the short-circuit key be alternately opened and closed, then if true balance has not been obtained, there is a distinct though slight sound heard when the key is open, but dead silence when the key is closed; this enables measurements to be made with a very much greater degree of accuracy than if the key were not employed. With reference to the Wien bridge, the authors point out that when a test is made with that bridge, under certain conditions when the experimenter approaches close to it the balance is often upset. Mr. Hay has for some time past adopted a very simple device to overcome that difficulty; the induction coil which is used to give the alternating currents is divided into halves, and the two halves are connected in series, and the junction put to earth; also the junction between R_4 and C is put to earth. By this device any influence resulting from the person making the test being near the bridge is entirely eliminated, and the test may be made with absolute accuracy.

Mr. Addenbrooke. Mr. G. L. ADDENBROOKE: I have read this paper with mingled feelings. I have myself been working on this subject a considerable portion of my time for the last two years besides what I did before, and have now completed the paper that I mentioned when discussing Mr. Rayner's paper. It traverses much the same ground, but between a periodicity of 1 period in 5 seconds and 50 periods. In that way I have got a range of periodicity of something like 1 to 200, and I have been able therefore to develop these curves in, I think, an interesting portion of their length, because they go down to the point which Mr. Kempe has referred to, the continuous-current value. It has always been my ideal to get to this point, and as I have been, through the kindness of Major O'Meara, in communication with the Post Office on the subject for some time, I think they and some other friends who know my results are agreed that it really is at the base of these curves that we get the origin of those actions which afterwards develop into the actions which Dr. Fleming has shown us to-night over the telephonic range of periodicities. The authors have dug out a great deal from a range of 5 times in the periodicity, considering the nature of the task. As regards the development of the phenomenon and the way of regarding it, I think it will be found there is much similarity in the way in which the argument has been developed by me,* to that adopted by the authors of this paper. I have taken rather a different line, which I will not go into now, but it also brings us down to the point which Dr. Fleming has developed, that these losses can at telephonic frequencies be roughly divided into two classes: one nearly constant and one varying directly with the periodicity. If, however, we come down nearer to the origin of the curves, one of these quantities, the one that Dr. Fleming takes as constant, also becomes variable, and I think the study of the variations of this factor will show us a great deal about the action occurring in dielectrics, because I fancy that this is practi-

* *Electrician*, vol. 68, p. 829, 1912.

Mr. Addenbrooke.

cally the phenomenon that we get on the galvanometer and which is usually called absorption. In going down to 1 period in 5 seconds I have been hoping that with a modern quickly-working galvanometer I would be able to make the two curves overlap, and I think it can be done. Mr. Crawley, who has given me great assistance in this matter, has devised a rotating commutator to work in connection with the galvanometer by which we hope to get fairly quick additive results and to see if we cannot overlap the curves and find out where any difference comes in.

This brings me to the first point in Dr. Fleming's paper which I wish to criticise, viz., the continuous-current resistance. I agree in this matter with the remarks of Mr. Kempe. I myself, working about in all sorts of ways for the best method of representing these results and to find a fundamental point from which to develop one's curves, have come down to the continuous-current resistance, or the loss it represents at a given continuous pressure, as the best basis. I have been anxious to do something of this sort for a long time, because I feel from my knowledge of cable work that cable men will never pay the attention to these phenomena which I think they deserve until they can connect them directly with their own results. Such a connection is also important for another reason. Mr. Rayner, in a recent paper * gave a list of 250 papers relating to measurements on this subject—chiefly with continuous currents—many of which are most valuable. But from some estimates I have made I have come to the conclusion that even if we take the papers in *Science Abstracts* alone there are probably not 250 but at least 500 papers on this subject, without including all the work that was done on dielectrics before *Science Abstracts* began. These papers at present are like a great mass of stones thrown together, some of them beautifully carved but without any architect's plan. They are nearly all by able men, for nobody touches dielectrics without considerable training. Fitzgerald once said that it was the most interesting but the most unremunerative subject which anybody could touch. I thought at one time that perhaps by collating these papers it might be possible to make something of the building, but workers get tired of the subject and go on to some more profitable one and leave it. Finally I found the only way was to take up experimenting, and I have gradually come down to the fact that the continuous-current resistance is the best basis as a standard for working my curves up from a low periodicity—a periodicity, in fact, at which the losses are very near the losses due to the continuous-current resistance alone. This brings us to the question of absorption. I may say that these losses will be found with consideration not only at telephonic frequencies but at all frequencies. For instance, a frequency of 2–3 is that at which the Atlantic cables are worked. Then we get all sorts of telegraphic frequencies up to 15, which Mr. Kempe told me not long ago was about the Wheatstone frequency. Next at 15 $\sim$ we get a frequency which is used for heavy railway work, and so on up to

* *Journal of the Institution of Electrical Engineers*, vol. 49, p. 3, 1912

Mr. Addenbrooke.

25, 40, 50, and 60, so that results over this range cover a very large portion and present many interesting and useful points of practical engineering. Many of Dr. Fleming's results compare on the lines given within a small percentage with those I get at about 50 ∿, so that it seems established that it is possible, at any rate with good dielectrics, to carry those curves up without much alteration from fairly low alternating-current periodicities to 700 ∿, and then to over 4,000 ∿, which I think is a remarkable result.

Communicated: Since I have had more time to study this paper I have come across several points about which I cannot at present feel comfortable. Without going into the question of theory on some points of which I feel doubt, as it is developed by Dr. Fleming, let us turn to page 351 of the paper, where the authors give their reasons for thinking that condensers simply made of dielectric sheets interleaved with tinfoil will give correct results for the actions occurring in the dielectrics themselves.

Before starting the investigations contained in the paper to which I have alluded, I held, tentatively, somewhat similar views, but I determined to submit the question to experiment before basing a serious amount of work on the reasoning. The result was that, using my electrostatic method, by which such actions are much more easily followed than by the bridge method, I found such variations, particularly in the apparent capacities shown, that I came to the conclusion that however valuable such results might be as showing how a condenser of a given dielectric behaved under the given conditions, the results could not be regarded as scientific results showing what happened in the dielectric itself, and that although in some cases I used a much greater compression than it seems to me could be secured by the authors' method, although in some cases I adopted the further precaution of blackleading the surfaces of the dielectric. Frankly, I do not consider the arguments of the authors are a complete statement of their problem, nor do I think it likely that there is such a change of condition between their periodicities and mine, that the precautions I found necessary at 50 ∿ can be neglected at 920 ∿. Though they do not explicitly say so, the authors appear to assume that surface leakage and conduction obey the ordinary Ohm's law. But this is by no means the case (I have recently sent in a paper to the Physical Society dealing with this point). There are also other points which I cannot take up without going into questions of theory, but which I have dealt with in the paper I have sent in to the Institution. I cannot help thinking that reasons of the above character must account for the dielectric coefficient of mica obtained by the authors. This does not agree with the very careful determination made by Curtis, of the Bureau of Standards, working at 1,200 ∿, which overlaps the authors' periodicity. Curtis makes only a very small difference in the capacity at 50 ∿ and 1,200 ∿ and my own results at 50 ∿ agree pretty closely with those of Curtis, making the dielectric coefficient about 7, which agrees fairly with the best determinations for good mica by the

usual methods. I cannot help viewing a dielectric coefficient of 4 with considerable suspicion. Somewhat the same reasoning applied to the figures relating to celluloid, but this is a more complicated matter; it may probably also affect the results for crown glass, and for pure Para rubber with gutta-percha, my results extended agree fairly with Dr. Fleming's, also with the previous results of Mr. Jacob. I cannot also help thinking that some of the curious temperature effects the authors show are due, at any rate to a considerable extent, to surface effects and not altogether to actions occurring in the dielectric. I have got somewhat similar results when testing covered wires, but under circumstances which I think may be most reasonably interpreted as surface effects, since entirely different results were obtained with what was presumably exactly the same dielectric. Dr. Fleming has suggested that the authors' results are worthy of further investigation, in which I cordially agree. If such investigation is undertaken and instead of building condensers of sheets of dielectrics and tinfoil held between glass plates bound together with silk ribbon, the method is used which Curtis found necessary, I shall be surprised if a good deal of modification in the results obtained is not shown. Curtis found that the only way to secure consistent results was to use two solid metal plates carefully surfaced, instead of the glass plates, and to use strong metal screw clamps to compress the leaves of the condenser together, instead of the silk tape used by the authors. He also coated the edges of the dielectric with paraffin. It is curious that neither the authors, nor Mr. Rayner in his paper or list of papers, refer to the work of Curtis,* to which Mr. Trotter kindly drew my attention. Mr. Addenbrooke.

Mr. E. H. RAYNER (*communicated*): The simulation of the dynamics of an electrical circuit containing a condenser not merely to a single condenser and a resistance, but to two condensers and resistances forming circuits of very different time constants, is a very interesting idea, and helps greatly to crystallise our rather nebulous conceptions on absorption. But why stop at two circuits? If it were possible to draw curves of potential and current in a condenser circuit to a sufficient degree of accuracy we should expect that a large number of such condenser and resistance circuits would be required. Still, as a working hypothesis the first two terms of such a series would probably be found sufficient, if experimental results are found capable of quantitative analysis on such a theory. In discussing instrumental methods, pages 345–347, the authors state that as their condensers had an impedance of about 100,000 ohms, resistances of this order would be required in the ratio arms of a Wien's bridge for proper sensitivity to be obtained. This would only be so if the telephone circuit had a like impedance. As, however, the telephone had a resistance of but 2,000 ohms and an impedance of the same order, it is obvious that very much lower resistances would give greater sensitivity than resistances of 100,000 ohms. In fact, 10,000 ohms or less would be probably found far better, which makes a resistance bridge a Mr. Rayner.

* *Bulletin of the Bureau of Standards*, vol. 6, p. 431, 1910; and *Science Abstracts*, vol. 14, A, No. 1,571, 1911.

Mr. Rayner. much more practicable affair. Moreover, while reducing the strain of observation the accuracy of observations could have been much increased had the authors' capacity bridge been arranged more on such lines. The capacities C_3, C_4, of impedances of the order of 100,000 ohms might similarly have been increased several fold with advantage, in view of the low telephone impedance employed. The possibility of winding telephones with a resistance considerably in excess of that of the highest commercial instruments, such as has been used by the authors, is of great importance for measurements of this nature on condensers of the order of 0·001 microfarad. Such modifications as are here suggested would have been found especially useful in the measurements on the materials of low power factor. That the limit of the authors' arrangement was reached is shown, for instance, by the measurements on paper, where it will be seen that the first figure, Table VII., is often quite indefinite. Of course the power factor is very low; but from a commercial point of view these and other materials of very low power factor are by far the most important tested. The number of significant figures obtainable cannot be too many, as improvements in material and treatment of such insulating media depend on the accuracy of such measurements. Another important experimental difficulty is caused by distributed capacity between various parts of the circuit and surrounding objects, notably between the observer and the telephone. The authors seem not to have earthed any point of their bridge system, but to have earthed a point on the previous filter circuit. There remains, however, a considerable effect from this cause, which is enhanced by the low value of the capacities used, and which is allowed for by reversing the bridge connections and taking the average. This is doubtless generally sufficient; but the magnitude of the difference may be considerable, as is shown in the last column of Table IV., and it would appear to be likely to give more trouble when testing circuits of lower power factors than shown by the glass of which the details are given. There is a method by which it might be eliminated, which is "virtually to earth" the telephone circuit. The principle of "virtually earthing" a given point on a circuit is also useful in many continuous-currrent as well as alternating experiments when possible leakage and electrostatic forces are likely to cause trouble. As applied to Wien's bridge, it is described by K. W. Wagner.* This is done by making up a third circuit of equal time constant in parallel with the other two. The "telephone" point of this third circuit is earthed, and no disturbance can then take place due to capacity currents between the observer and the telephone. By this means, using capacities of the order of 0·01 microfarad, and probably a higher voltage than that employed by the authors, Wagner states that the power factor of a paper condenser of the order of 0·007 can be measured to about 0·5 per cent., whereas the authors' first figure is somewhat uncertain.

The authors give for paraffined paper 0·007–0·008 for the power factor agreeing with the above value. Mica is much less than this,

* *Electrotechnische Zeitschrift*, vol. 40, p. 1001, 1911.

and the difference is generally regarded as due to the comparative imperfection of paper as a dielectric. It would be interesting to know if it is possible to build condensers approaching those made of mica in lowness of power factor, by substituting silk for paper. By this means large condensers equal or nearly equal to mica might be made at considerably less expense. The very small effect of interposing mica, a material of practically infinite ohmic resistance, on the energy loss occurring in imperfect insulators is well illustrated in condensers A and C, Table IX. As I showed a few weeks ago, the heat generated in such a circuit at a high voltage is quite sufficient completely to scorch such materials as the oiled cloths commonly used as insulation. The results of the experiments on vulcanised rubber and on gutta-percha are naturally of the greatest interest, and I hope the authors will continue their experiments on commercial rubber cables, and see whether other samples not only have a minimum at a similar temperature, but also whether that minimum is generally so low as is shown in Fig. 27. In my experiments mentioned on page 388, in which I pointed out the negative temperature coefficient of the power factor of gutta-percha, I made no attempt to go beyond the temperatures to which submarine cables would be exposed, and at the frequency of 50 the curves which I obtained differed but little from a straight line. Some comment on the results given in Table XXIV. for the power factor of a twin-wire gutta-percha cable, which seems to have a very different value when straight and when coiled, 0·029 and 0·045 would be very desirable. If the effect is due to mechanical strain on the insulating material it is of great importance. The results given for sulphur exemplify the difficulties experienced when the experimental method is pushed to its limit. The authors might be able to obtain more accurate values for sulphur (and for mica) by testing condensers of considerably larger size. By using a Wien's bridge with equal resistance arms of about 2,000 ohms, the three air condensers could be put in parallel in the fourth arm. By this means the impedance of the bridge could be much reduced with considerable increase in sensitiveness and gain in accuracy at these very low power factors. **Mr. Rayner.**

Mr. W. DUDDELL (*communicated*): The subject is a most important one, and the authors have covered so much ground, that I will in the discussion confine myself to two main points: first, the method of test; and secondly, the results for one or two of the dielectrics. With regard to the method of test, the authors have very rightly adopted a bridge method rather than a wattmeter one; although it is quite possible to measure with a wattmeter the very small loss in a standard ½ microfarad condenser, it seems impracticable except at high voltages and using an electrostatic wattmeter to work on samples with a very small capacity. I am not certain, however, that I agree with the authors in having adopted two condensers instead of two non-inductive resistances for the bridge arms. I have myself for a long time been using the resistance bridge method for measuring power factors of small condensers, such as a foot or two of flexible wire, and I have not **Mr. Duddell**

Mr. Duddell.

found it necessary to use very high resistances, although I have made measurements on condensers quite as small as those mentioned by the authors. If the authors will interchange the alternator and telephone in Fig. 7, quite good sensibility can be obtained when the resistances R_3, R_4 are of moderate value, provided the resistances will stand the 10 volts or so which is applied to the bridge. If woven resistances are used so that the little self-induction and capacity that they possess is uniformly distributed, the error introduced becomes extremely small. In my own tests I have preferred to use an alternator, which gave a very good sine wave, and a vibration galvanometer in place of the telephone, but I must admit that the highest frequency I have worked at has been some 1,800 periods per second. Where such very high frequencies as 5,000 per second need not be attained, the ordinary method with a plain good sine wave alternator and a vibration galvanometer gives excellent results, and is easy to work. I can appreciate the extremely trying nature of making the tests as described by the authors, and I think they are to be complimented on the satisfactory results they have obtained under such conditions. The telephone in comparison with the vibration galvanometer as an indicator is a very inferior instrument. It requires some considerable practice to feel which way one ought to go in making one's adjustments, when one has to estimate when a sound is increasing or decreasing, whereas there is not the slightest doubt whatever in one's mind when one observes the movement of a spot of light. The authors have referred to the difficulty of the condensers interfering with one another, and to the presence of the observer's body affecting the results. If the condensers have been properly screened, I hardly think this would have been the case. One precaution which materially assists in tests of this kind is to connect a potential divider across the terminals of the alternator, and to earth the slider. By adjusting the slider, any desired point of the bridge circuit can be brought near earth potential, and the effects of leakages and spurious capacities minimised. In many cases I have found that the best results are obtained by so adjusting the slider, that the vibration galvanometer is at earth potential. The results obtained by the authors are extremely interesting, and in general show how little the power factor of certain dielectrics, such as glass, dry paper, and mica depends upon the frequency, and how much it is affected by temperature.

The case of paper is especially important owing to the large use that is made of this substance, not only for "dry core" telephone cables, but also for condensers and high-tension mains. A number of tests I have made on good quality paper condensers show that the power factor is generally well under 0·5 per cent., which is in fair agreement with the authors' results for paraffined manilla paper carefully dried (Table II.). Power cables, on the other hand, generally seem to have power factors of the order of 1¼ to 1½ per cent.; possibly this additional loss is due to the presence of the oil. The author's figures for mica indicate how extremely low the power factor of this substance is. It is possible to obtain good mica condensers where the

Mr. Duddell.

power factor does not exceed 0·1 per cent., and which apparently remains practically unaffected by frequency over very wide ranges. A very complete series of results has been given by Grover in his paper, "Simultaneous Measurement of the Capacity and Power factor of Condensers.* In contradistinction to these bodies, which behave comparatively simply, the authors show a most extraordinary effect in vulcanised rubber, namely, that its power factor is a minimum in the neighbourhood of 20° C., that is to say, at about atmospheric temperature. It would be extremely interesting if further tests could be made to confirm these results. In the past there has been a considerable amount of discussion before this Institution on the power factor of rubber cables. On the one hand, it was maintained that this power factor rarely exceeded 2 per cent., whereas certain other writers attributed much higher values to it. At that date I made a number of tests on the power factor of rubber cables, either in the maker's works, or laid in the earth, and all these came out at the order of 2 per cent., which is several times the minimum value the authors find. It is an extraordinary result that a drop of temperature to the freezing-point will, even at the lower frequencies used by the authors, more than double the power factor. The peculiar properties of vulcanised india-rubber brought to light by Professor Fleming in this paper, and by Mr. Rayner in a paper lately read before the Institution,† seem to indicate that a great deal more work requires to be done on this material, which would well pay for doing, in view of the many curious faults that come to light from time to time on rubber-insulated mains. With regard to gutta-percha, at the time of Major O'Meara's paper before the Institution, I carried out a number of tests on the power factor of a length of gutta-percha cable that was kindly lent me by the Eastern Telegraph Company, and although the frequencies I used did not exceed 650, I think the results may be of interest as showing the shapes of the curves when starting from very low frequencies. A fairly long length, namely, 300 fathoms, was used for this test for reasons which have nothing to do with the testing of its dielectric. The cable core was covered with brass teredo taping, and the condenser formed between the core and the brass tape was tested on the bridge at frequencies varying from about 5 to 635. The results are shown in Fig. B, which gives a change of capacity with frequency as well as the change of power factor. It must be remembered, when testing a long length of cable like this, that a certain amount of power is dissipated in the copper conductor owing to its having to carry the capacity current. This has been corrected for in the figure. It is to be noted that the power factor at 600 frequency and 14° C. is 0·0208, and is slightly rising, the slope being such that at Professor Fleming's lowest frequency of 920, the power factor might come out at 0·022, which is in fair agreement with his figure of 0·020 at 15° C. Calculating S/C from my curve, it comes out at 108 at the standard frequency, and

* *Bulletin of the Bureau of Standards*, vol. 3, No. 3, 1907.

† *Journal of the Institution of Electrical Engineers*, vol. 49, p. 3, 1912.

Mr. Duddell.

this was the figure and test I had in mind when making the remarks closing the discussion on Major O'Meara's paper. It is very interesting to note how rapidly the power factor of gutta-percha decreases below about 200 frequency, and at the same time the capacity rises.

The authors have done a good service in again drawing attention to how easily a power factor measurement of a piece of the cable can be used to determine the value of the leakance which is required for

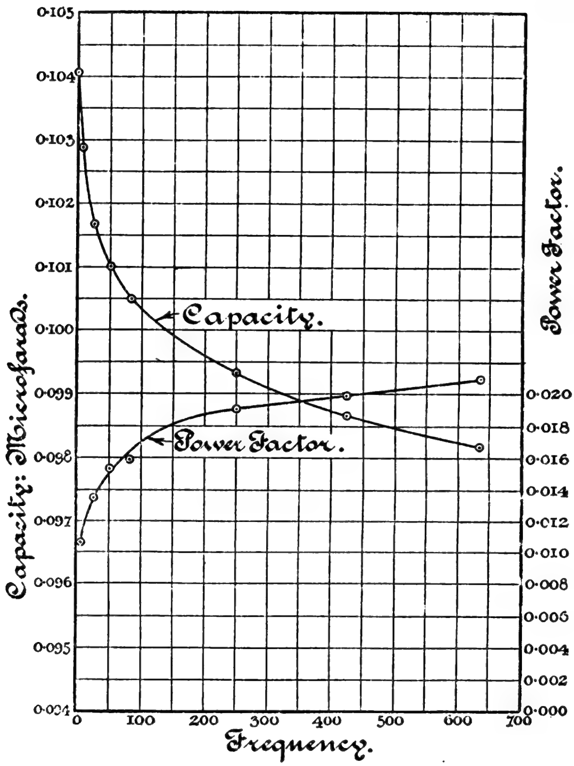


FIG. B.

use in the calculation of attentuation constants. As I pointed out in closing the discussion on Major O'Meara's paper, if the capacity per mile be multiplied by the power factor and p, we have the required leakance. For instance, for the Danish cable of which the data were given in Appendix VIII. to Major O'Meara's paper, the capacity per knot is 0·253 microfarad, and the power factor of gutta-percha may be taken at 2·1 per cent., so that at 750 frequency the leakance per knot is $0{\cdot}253 \times 10^{-6} \times 2{\cdot}1 \times 10^{-2} \times 2 \times \pi \times 750 = 2{\cdot}5 \times 10^{-5}$, which is very

close to the $2 \cdot 4 \times 10^{-5}$ given for the leakance of this cable in the table. When testing the power factor of the dielectric of a piece of cable, it should be borne in mind that there is a correction to make for the I^2R loss in the cable produced by the capacity current. The authors do not refer to this correction in their paper, and in the case of the cables they tested the correction is too small to matter. When long lengths are investigated, however, this correction may become very important. It is quite easily made by deducting from the observed power factor at any frequency the quantity $C R p$, where R is $\frac{1}{3}$ of the loop resistance of the cable under test; in other words, the cable behaves like a condenser having in series with it a resistance of $\frac{1}{3}$ its total resistance. All through the paper the authors have referred to an alternating-current conductivity. I must say that I feel that this way of looking at the quantity rather tends to confuse the issue. What we really observe is that a certain amount of power disappears, and I think that the old way of looking at it as a power factor is much simpler especially as, when looked at from the point of view of having a power factor, we obtain numbers which do not largely depend upon the frequency, whereas when converting it into an alternating-current conductivity we obtain numbers which vary greatly with the frequency and which are very difficult to retain in our minds. For instance, the fourth conclusion that the authors come to really amounts to no more than saying that there is in most dielectrics a loss due to ordinary leakage, and a loss due to what is commonly called dielectric hysteresis, the former of which is independent of the frequency, and the latter proportionate to the frequency. As in most good dielectrics the leakage loss may for most purposes be neglected when working at high frequencies, we come to the usual conclusion that most of the high-class dielectrics possess a very nearly constant power factor. Mr. Duddell.

Mr. G. M. SHEPHERD (*communicated*): In regard to the tests on dry-core telephone cable it is noticed that the authors employed a length of 30 yards. Of course, in such a case of distributed capacity and high conductor resistance as a 10-lb. cable, the shorter it is the better, having due regard to difficulties in measurement. Tests have, however, been made at Telephone House on sections of this particular gauge of cable up to 400 yards at 800 to 1,000 ∿, and with capacities of this magnitude the precautions mentioned on page 347 of the paper are of much less importance. It was found that even greater lengths than 400 yards could be measured, providing that a correction was made for the distributive effects above referred to. This correction depends on the fact that the real value of the impedance of a cable with far end open-circuited is $Z_f = Z_0 \coth Pl$, Z_0 being the surge impedance, P the propagation constant, and l the length. Expanding this expression, and dropping higher terms when l is small enough— Mr. Shepherd.

$$Z_f = \frac{S - jpc}{S^2 + p^2 c^2} + \frac{r}{3} \quad \ldots,$$

Mr. Shepherd.

where S, c, and r are constants for length in question. This leads to the bridge equation for insulation resistance—

$$m = \frac{3\,Q^2\,R}{3\,P\,Q - r\,p^2\,k^2\,R\,P^2};$$

P and Q being ratio arms, and R the combined resistance of balancing and effective resistance of standard capacity k. If a correction of this sort is not made, the measured insulation at 800 ∿ goes very wrong indeed when the cable length reaches half a mile. If it be necessary to make tests upon still greater lengths of several miles and upwards, it would seem that no ordinary bridge observation is competent to determine S, and recourse must be had to the vector impedance method already referred to by Mr. Cohen. It is hoped that the authors will extend their research to dry-core and other cables of various types and sizes, as no doubt very considerable variations will be found to exist.

Mr. Coote.

Mr. J. F. COOTE (*communicated*): The figures given by the authors for vulcanised indiarubber and gutta-percha are of great interest, but it appears to me that the conclusion arrived at in favour of the former as an insulator will require confirmation from a much wider series of experiments before it can be accepted as applying generally. Only one quality of V.I.R. seems to have been tested, and it may be possible, considering the extremely variable composition of this insulator, both as to the number and the nature of its ingredients, that the particular samples tested by the authors, may have had some constituent to which the peculiar results found were due. In view of the results obtained in the case of sulphur, which show the power factor for that substance to be vanishingly small, it occurs to me that the V.I.R. in question may have contained a high percentage of sulphur, and that the results were, partly at any rate, due to that.

Some figures published by Mr. Jacob in an article entitled "Leakance in Loaded Telephone Cables,"* seem to show that V.I.R., so far from being superior to gutta-percha, is decidedly inferior. He gives the value of new V.I.R. core as 132, compared with 111 to 120 for gutta-percha, and moreover states that V.I.R. core about five years old has a value 240. Presumably the same V.I.R. is referred to, and if so, these figures show that a very considerable ageing effect exists with V.I.R., and the same may apply to gutta-percha, so that more information is needed on this point. It will also be evident from Tables XXIII. and XXIV. that in future, when giving values for V.I.R. and gutta-percha cables, the method of laying up the cores must also be stated, as this influences the result to such a marked degree. For instance, the authors compare the value $S/Cp = 0{\cdot}024$ at 750 p.p.s. given by Mr. Jacob for the Anglo-French (1910) cable, with the value 0·029 which they obtained for a twin-wire gutta-percha cable (Fig. 32), but it must be remembered the former corresponds more nearly to their single-pair

* *Electrician*, vol. 65, p. 532, 1910.

cable (Fig. 31), for which the value S/Cp would be about 0·103 at 750 p.p.s. (Table XXIV.), inasmuch as the diagonal cores which form each telephonic circuit in the Anglo-French cable, are separated by the jute yarn in the centre,* so that the agreement does not seem so very good. Mr. Coote.

Mr. A. WHALLEY: No doubt precautions were taken to prevent the vitiation of results by dust and finger-marks upon the small sheets of dielectric. Apparently a vacuum process was not used for the samples which were dried. The results for ebonite and vulcanised rubber are very interesting. Both substances contain rubber and sulphur, and I should like to ask, if the mixtures cannot be stated, whether the percentages of both rubber and sulphur, and also the specific gravity could be given? The ages of the samples are perhaps known also. Mr. Whalley.

Dr. J. A. FLEMING (*in reply, communicated*): It will not be necessary to answer at any very great length the remarks that have been made in this discussion. The general conclusions in the paper have not been invalidated, and some of the smaller criticisms seem to show that the speakers have not sufficiently considered the results and statements in the paper. Dr. Fleming.

In thanking Dr. Russell for his appreciative remarks, I may say that I entirely agree with him as to the necessity for revising some parts of the theory of telegraphic and telephonic conductors, so as to take into account the fact that the leakance is a function of the frequency. I am also in agreement with him as to the advantage of renaming the so-called "dielectric constant" the "dielectric coefficient." Why not call it the "dielectrivity" analogous to "resistivity," "conductivity," etc. Although certain combinations of non-absorptive condenser with constant resistances in series and parallel will approximately imitate the behaviour of an absorptive condenser, I have not yet been able to devise one which is an entire equivalent, and there is much in the structure of dielectrics which yet needs to come to light.

I am glad to find that Mr. Cohen substantially confirms our measurements with paper-insulated cables. His criticism of the word "selected" for "rejected" on page 339 of the paper has already been noted as probably valid.

It is pleasing to learn from Major O'Meara that some parts of our work may be important to telegraphists. There is no doubt that perfect desiccation of paper is essential if it is to be used to the greatest advantage as a dielectric for telephone cables. With regard to Mr. Campbell's remarks, I have no wish to disparage any method of creating the pure sine curve voltages necessary for telephonic tests which he has found useful. In all laboratories more limited in their power of acquiring apparatus than the National Physical Laboratory, a large part of the difficulties consists in "making do" with the apparatus at hand, and the *res angusta domi* generally determines what we are to use. Whatever method is used must give a pure sine curve

* *Proceedings of the Institution of Electrical Engineers*, vol. 46, p. 336 (Fig. 13), 1911.

Dr. Fleming.

E.M.F., as the theory of the bridge given is not otherwise valid. My preference is for a simple sine curve alternator of variable frequency, but failing that, our method of resonating out the harmonics of any alternator is simple, cheap, and efficient.

Mr. Kempe's contribution to the discussion calls for a slightly more extended reply than those remarks which preceded it. He challenges my remarks concerning the inadequacy of the direct-current I.R. test, and yet at the same time, in his own first sentence, he agrees with me. I said that, except as a test of dielectric strength and a means of revealing defects of manufacture, it has very little scientific value. Mr. Kempe says he totally disagrees, and he then proceeds to say that the essence of the test is to discover defects of manufacture. This is precisely what I say; but I also say that the direct-current I.R. test is no use to enable the real value of S/K or S/C to be found. I have met with cable electricians at cable works who assumed that S/C could be calculated by taking the reciprocal of the product of the I.R. resistance and the constant-current capacity of the cable both per mile, and that is erroneous. No tests with direct current will give the correct value of the quantity S/C which is so essentially a characteristic of the cable as a telephone conductor.

The importance of this quantity is proved by Mr. Kempe's next remark, where he refers to the enormous improvement which Messrs. Siemens have made in the value of S/C for gutta-percha cables, as instanced by the great reduction from 114 to 12 in the case of the last Anglo-Belgian cable. Mr. Kempe's next criticism would not have been made if he had taken the trouble to read our paper a little more carefully. He says it is stated on page 399 that the *specific resistance* of gutta-percha varies from 3·5 to 7·0. Nothing of the kind is stated. What is said is that the value of the *dielectric constant* or dielectric coefficient of gutta-percha is given in various books as having values between 3·5 and 7·0. Mr. Kempe has only to refer to various well-known tables of physical constants or to papers in *Science Abstracts* to see that this is correct. Hence when he assails the statement as ridiculous he is fighting a phantom. The reason for these various values is to be found in the very different times of charging and qualities of the specimens used. Hence all Mr. Kempe's subsequent remarks under the heading are invalidated, since he is not criticising what is actually in the paper, but what he has read into it by mistake.

I am afraid Mr. Addenbrooke has not followed very carefully the proof I gave of the reason why perfect contact between the dielectric and the metal electrodes is not nearly so serious a cause of error in the case of alternating currents as in the case of continuous currents, or else he would not have seen reason to disagree with it. I think that Mr. Addenbrooke's opinion, unsupported by proof, is not a sufficient reply to the mathematical arguments given in Part I. of our paper. Mr. Addenbrooke criticises the dielectric coefficient given by us for mica, and is apparently disposed to quote Curtis's results

against ours. It cannot be too often or too emphatically remarked that in substances of complex composition, such as mica, glass, gutta-percha, indiarubber, etc., no precise measurements of a dielectric coefficient for a substance, as opposed to a specimen are possible. Values for the dielectric constant of mica given by various investigators vary all the way from 4 to 8. This kind of criticism is a good example of the manner in which the broad issues or aims of a paper may be lost sight of in a discussion, and immaterial numerical differences dwelt on or magnified. The chief result of our paper is that the conductivity of dielectrics for alternating currents is a nearly linear function of the frequency, and hence affects the important ratio S/C, and is also greatly affected by variation of temperature. We hope we have provided a simple and easily applied method of determining it, and that the results will be useful to cable manufacturers. Much useful matter has come to light in the discussion, and the remarks of Mr. Rayner, Mr. Shepherd, and Mr. Coote are of considerable interest. Dr. Fleming.

Proceedings of the Five Hundred and Thirty-ninth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, 18th April, 1912—Dr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting, held on Thursday, 28th March, 1912, were taken as read, and confirmed.

Messrs. A. J. Graham and F. T. Hall were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Member.

Arthur Smith Black.

As Associate Members.

John George Burchell.
Arthur James Dickinson.
James Edward Fletcher.
James Sherwin Hasdell.
William Innes.
Ernest John Mayne.
Thomas B. Nutter.
Percy Charles Pocock.
Max Ernest Pyser.
Francis Blewett Shaw.
Tom Vincent Smith.
Leslie Wallis White.

As Associate.

Khaja Ismail.

As Students.

David Edward L. Barnes.
George Harold Barraclough.
William Arthur Barratt.
Harold Alexander Bower.
George Collyer.
Francis Joseph Delves.
Noel Elkington.
John Eaton Griffiths.
Francis Lewis Heath.
Peter Jackson.
Edwin Jennings.
Alban Aloysius Kilduff.
John Bernard Murray.
Horace Stephens Ripley.
Reginald Hesslewood Robinson.
Christopher Young.

Donations to the *Library* were announced as having been received since the last meeting from W. Aitken, A. Bursill, A. Constable & Co., Ltd., F. H. Davies, J. R. Dick, The Electrician Printing and Publishing Co., Ltd., F. Fernie, R. K. Gray, The Iowa Engineering Experiment Station, C. Matschoss, W. B. Shaw, The U.S. Bureau of Mines, and

The U.S. Bureau of Standards; and to the *Museum* from The Eastern Telegraph Company, Ltd., and Dr. S. P. Thompson, F.R.S., to whom the thanks of the Meeting were duly accorded.

The PRESIDENT then read the following nominations made by the Council for the election of Council and Officers for the year 1912–13 :—

MEMBERS NOMINATED BY THE COUNCIL FOR OFFICE, 1912–13.

As President.

New Nomination ... W. DUDDELL, F.R.S.

As Vice-Presidents.

Remaining in Office { MAJOR W. A. J. O'MEARA, C.M.G.
J. F. C. SNELL.

New Nominations... { W. JUDD.
C. H. MERZ.

As Honorary Treasurer.

For Re-election ... ROBERT HAMMOND.

As Members of Council.

Remaining in Office {
H. DICKINSON.
J. S. HIGHFIELD.
H. HIRST.
B. M. JENKIN.
J. E. KINGSBURY.
P. V. MCMAHON.
R. K. MORCOM.
S. L. PEARCE.
H. FARADAY PROCTOR.
C. P. SPARKS.

New Nominations... {
F. GILL.
A. RUSSELL, D.SC.
W. RUTHERFORD.
A. H. SEABROOK.
ROGER T. SMITH.

As Associate Members of Council.

Remaining in Office { S. MORSE.
H. E. WIMPERIS.

New Nomination ... A. B. ANDERSON.

The evening was occupied in an adjourned discussion on "The Causes preventing the more General Use of Electricity for Domestic Purposes."

Proceedings of the Five Hundred and Fortieth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution, Victoria Embankment, London, W.C., on Thursday, 25th April, 1912—Dr. S. Z. DE FERRANTI, President, in the chair.

The Minutes of the Ordinary General Meeting, held on 18th April, 1912, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

R. P. Howgrave-Graham.
Harry A. Nevill.
James E. Taylor.

From the class of Associates to that of Associate Members :—

Andrew S. Gray.
William Lang.
Stanley Rudd.
E. Counsell Wansbrough.

From the class of Students to that of Associate Members :—

William Brooker.
Laurence H. A. Carr.
Charles N. Good.
E. F. Hetherington
James N. Hindle.
Geo. D. L. Horsburgh.
James C. Hutton.
Kurt John Nebel.
Frank Parkinson.
Joseph P. Quinn,
William E. Russell.

THE THIRD KELVIN LECTURE.

THE WORK OF LORD KELVIN IN ELECTRICITY AND MAGNETISM.

By Professor H. DU BOIS, Ph.D.

(*Delivered 25th April*, 1912.)

Lord Kelvin's scientific activity extends over two-thirds of a century, and forms the connecting link between the French school of Louis Philippe's time and our own twentieth-century achievements in mathematics, physics, and engineering. It was a period of unusual length, though infinitesimal when compared to the geologic unit of a score of million years which he so often indulged in. He was the last of the great men to whom we owe the evolution of science and industry in the middle of the past century, which transformed the foundations both of scientific thought and of material life. Irish wit, Scotch logic, and English energy were harmoniously blended in Lord Kelvin, raising him to the rank of the United Kingdom's worthiest representatives.

When one of our leaders has departed from amongst us it is customary to organise a memorial meeting. As certain transcendental functions are only expressible by means of series, so this Institution felt that Kelvin's life-work could only be adequately treated in the course of successive lectures. The terms of a good series ought to diminish as they proceed; it is to be hoped that the third term will not shrink too much, compared with the one preceding it. The second Kelvin lecturer was in a position to promise a beautiful solution of the immense and difficult undertaking of the first lecturer in surveying the life of Lord Kelvin. I think we may now all join in thanking him for giving us, besides his lecture, such a splendid book, containing an inexhaustible store of information for future lecturers; personally, I am also much indebted to him for a number of very useful hints.

The second lecturer went out to sea with Kelvin, as was fitting, and gave a most interesting survey of our great captain's oceanic work. It was only natural that your Council should next wish a tribute from beyond these islands to the memory of him who died as its President. I highly appreciate the honour of being selected for this task, though more than twenty-five years have elapsed since I left Glasgow University. I was rather afraid at first that nothing could be said that had not already been mentioned in some perhaps better way. However, a month's

re-reading of Kelvin's papers brought me to the opposite conclusion ; the total sum of material is so overawing that the series of lectures may progress for many more terms before exhausting the supply.

My work in Kelvin's laboratory fell in a period when electricity and magnetism had full sway, and this influence has since proved lasting; I will therefore attempt, at least superficially, to review his work in that science. His Presidential Address* on "Ether, Electricity, and Ponderable Matter," mentions "the growing desire of the members to know something of the molecular or dynamical theory of electricity and magnetism." This may be my excuse for not restricting myself to the practical or engineering point of view. At the express desire of your Committee I shall also try to describe some of the later developments of Kelvin's teaching and ideas by his pupils and followers; this may be said to honour his memory no less than a review of his own work, and will certainly furnish material for an infinite succession of lectures.

I.

Electrostatics was Lord Kelvin's first love, so he told the members of this Institution twenty-three years ago. It was first alluded to somewhat incidentally, in connection with the motion of heat, in the third paper signed "P. Q. R." (1842). Two years before, at the age of sixteen, he had read through and mastered Baron Joseph Fourier's "Théorie Analytique de la Chaleur." This work, classical not so much for its subject as for its method, made a profound impression on the mind of the youthful reader, who must have felt at once its generality and wide scope. Half a century afterwards he used to feed us on Fourier, harmonic analysis, and kindred subjects with keen delight. After his public start as a mathematician, he now first revealed himself as one of our brotherhood—a most potential electrician in the word's double sense.

The following years witnessed a series of papers on the mathematical theory of electricity in equilibrium, containing many fundamental theorems on distribution, electrostatic induction, non-conductors, etc., and preparing the path which led from the ancient action-at-a-distance methods to the Faradic and Maxwellian point of view. A fresh impetus was given in this direction by his perusal (in 1845) of Green's "Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism."

A result of a less abstract nature was the theory of electric images and reciprocal radii. Later on he was led to calculate the electrostatic capacity of a Leyden phial and of an insulated wire in the axis of a cylindrical conducting sheath, problems of eminently practical importance in submarine telegraphy. The construction of condensers, or, as he afterwards called them, air Leydens, after the ancient Dutch University, received his attention as late as 1892.

The subject of practical electricity, moreover, appears to have drawn Kelvin's attention about the year 1860 in the form in which it

* *Journal of the Institution of Electrical Engineers*, vol. 18, p. 4, 1889.

primarily had to be faced by mankind, viz., atmospheric electricity. The first impetus was given by his visit to Kreuznach, where he acquainted himself with the regular aero-electrical observations of Dellmann.

The general principle of collection, whether by water or by fire, was clearly understood and expressed by him. If we conceive a conductor first belonging to the earth to become insulated and to be made to throw off, and to continue throwing off, portions from an exposed position of its own surface, this part of the latter will quickly be reduced to a state of no electrification; the whole conductor will be brought to such a potential as will allow it to remain in electrical equilibrium in the air. The potential throughout the insulated conductor is brought down to that of the equipotential surface in the surrounding air which passes through the point from which matter breaks away. This applies in the first place to the water-dropping collector. As regards burning flames we now know that their behaviour is not so simple; as early as 1889* a paper was published on electrification of air by flame. Kelvin considered the earth as a spherical Leyden jar; the resinous (negative) charge residing on its surface, while the vitreous (positive) electricity occupies the rarefied layers at altitudes of 10 kilometres, or even more, above the highest terrestrial peaks; his absolute measurements of the gradient showed its mean value per metre to be of the order of our average house voltages, say 100 volts, though fluctuating immensely both in sign and numerical value. It is of interest to railway engineers that the steam from a locomotive funnel was always found negatively charged, and that from the safety valve always positively. Kelvin's self-recording atmospheric electrometer was brought into regular operation at the Kew Meteorological Observatory in the beginning of 1861. For half a century onward an immense amount of records were compiled all over the world of interest chiefly to the meteorologist, and, in a lesser degree, to the agriculturist. It is only in our days that man's conquest of the atmosphere brings such work within the range of the practical engineer; it is of importance alike for wireless telegraphy, ballooning, and aviation. Conversely, the latter may also vastly extend our knowledge of the atmosphere's electrical behaviour: a result which might have led Lord Kelvin enthusiastically to welcome our modern man-bird instead of rejecting him as a dynamical impossibility.

In connection with atmospheric electricity, the first attempt was also made to measure the absolute E.M.F. required to produce a spark in air at ordinary pressure between slightly convex parallel metal plates at different distances. This is interesting not so much on account of the experimental result as for the clear definition in absolute measure of the various quantities involved. The spark-length did not exceed 1·5 mm., corresponding to 6,000 volts roughly. The limiting value of the electrostatic force preceding a spark was found to be not much less than 120 electrostatic C.G.S. units, or, say, 35,000

* Kelvin, *Mathematical and Physical Papers*, vol. 6, p. 1.

volts per centimetre. This was shown to correspond to a stress along the lines of force—in the Maxwellian sense—of about 0·6 gramme-weight per cm.², which was considered electrically to relieve the usual atmospheric pressure of nearly a kilogramme-weight per cm.². At that time the available apparatus consisted of Coulomb's torsion balance, various electroscopes (Peltier's, Bennet's, Henley's, Bohnenberger's, and others), and the electrometers of Dellmann, R. Kohlrausch, Riess, and Hankel. Though some of these have done, and are, in a modernised form, still doing good work, they fell short in sensitiveness, precision, and the possibility of absolute measurement. Kelvin saw that there was a demand for improvement and at once started to supply all that might be needed; in fact, this constitutes the beginning of his practical career as a designer and inventor, in which he was to achieve marvels. No doubt it had always been a good tradition that every experimental physicist who respected himself should give his name to one or two new instruments in connection with his work. The French school then particularly excelled in this branch, and a number of first-rate instrument-makers were established in Paris. Kelvin's short stay in Regnault's laboratory in 1845 must have influenced him in this direction and developed his natural practical instinct and geometrical insight. His combination of highest mathematical power, fertility of ideas, and attention to every practical detail was so exceedingly rare that the world will probably never witness it again.

At the Dundee meeting of the British Association in 1867, he reported very fully on his electrometers and electrostatic measurements. The heterostatic principle already embodied in Bohnenberger's electroscope was first applied in the divided ring instrument, the evolution of which soon led to the quadrant electrometer in its well-known form. In developing this and other instruments he had the good luck of being assisted by James White, whose share it is only fair to point out. This skilful optician had started in a very modest shop which was more and more enlarged as the number of hands increased, until in 1884 the firm removed to the fine works in Cambridge Street, Glasgow, and is now known under the name of Kelvin and James White, Ltd. James White died very soon after I came to Glasgow, and in 1884 the manager was Mr. David Reid. I well remember being taken to the small factory behind the optician's shop, then in Sauchiehall Street. The unceremonious way in which the professor moved about among the lathes was delightful; he instructed the workmen individually on every detail, thus keeping up their interest in the work, and did not forget to inquire how they had enjoyed a party on the coast to which he had invited all of them. It is this intimate contact between the calculating, inventing, and designing physicist and the executive organs which claimed such a large part in the elaboration of Kelvin's numerous instrumental devices; though originating from his innate kind-heartedness, it was no doubt also an important element of success. It cannot be said

that the modern tendency towards uniform output in all branches of such work at all encourages that useful and fatherly mode of proceeding.

The quadrant electrometer in many respects was a departure from orthodox instrument-making; it is conceived throughout in a truly original spirit. Instead of the usual slide with dozens of screws, we have "the one degree-of-freedom V-groove device"; the adjusting arrangement of the bifilar is elegantly simple, the gauge well adapted to its function. Great difficulties were experienced with the glass jars owing to the damp climate. If Kelvin had worked in the dryness of Continental or American winters, where one may move about fully charged over the laboratory floor, sparking as one shakes hands, the replenisher would never have been invented. This successor to the old Bennet-Varley doublers could only have its birthplace in the moist muriatic atmosphere of the good city of Glasgow. The quadrant electrometer soon proved a most useful addition to our stock of instruments; potential differences of about 1 volt could be heterostatically measured to $\frac{1}{4}$ per cent., the range being 5 volts or so, and $\frac{1}{100}$ of a volt being indicated in the most sensitive adjustment. The sensibility could also be graded, bringing up the range to 5,000 volts; it has also often been used idiostatically.

The importance of the instrument is well illustrated by the number of modifications proposed in the course of time to serve a variety of purposes, which were, however, not always improvements. The electrometers of Curie, Righi, Hallwachs, Elster and Geitel, and Dolezalek are among those most in use to-day. The quadrant electrometer is the prototype of the multicellular electrostatic voltmeter, independent of temperature, stray fields, and wave-form or frequency, and suitable for low voltage, say 20 to 500 volts. On the other hand, the high-tension vertical electrostatic voltmeter is adapted to voltages from 500 to 20,000 or even 100,000 volts. It now contains only one pair of quadrants, into which a movable vertical vane supported on knife-edges is idiostatically attracted; by the simple device of attached weights different ranges may be obtained.

The absolute electrometer and other instruments of its class were founded on the balance method described by Sir William Snow Harris in 1834. The attracted disk, supported by coach springs and surrounded by its guard-ring, form the principal feature of that well-known instrument, the use of which is naturally restricted compared with the quadrant. In connection with atmospheric electrical observations the portable electrometer was designed, which was used by the Arctic expedition of 1875. It was a light, compact instrument, the principle of which is, however, hardly applicable in modern electrometers for purposes of travel by land or sea or air. Finally, the standard electrometer was meant to measure easily and accurately differences of potential in arbitrary units, and the long-range instrument was intended for very high potentials corresponding to sparks up to 25 cm. in length.

Numerous attempts were made to apply the balance principle to practical purposes, and many shapes of the attracting pieces were tried. I well remember quantitative experiments with rings, spheres, cones, and other figures. In the electrostatic volt balances as now made metallic plates, hemi-ellipsoids, or pans are used in connection with a movable arm travelling over a scale, the voltage ranging up to 100,000 volts.

II.

Since Volta's and Galvani's time galvanic batteries had been handled by special methods; it was Kelvin's aim to make them amenable to electrostatic determinations—in fact, this was one of the reasons for designing the absolute electrometer. After a first publication in 1853, several preliminary experiments were made in the sixties with batteries of 100 to 450 elements; finally, in 1870, from experiments by Leitch and MacKichan with the best form of absolute electrometer, the E.M.F. of 1,000 Daniell's cells in series was found to be 3·74 electrostatic C.G.S. units. This is equivalent to an electrostatic attraction of 5·7 grammes-weight per 100 $cm.^2$ of two parallel plates at 1 mm. distance apart. From our present point of view this is pretty near the truth, considering that the E.M.F. of most cells varies by several per cent. with the concentration and the nature of the electrodes, and also with temperature, as was expressly stated by Kelvin, though the effect is small for the Daniell cell.

This question is nearly related to what was called at that time the mechanical theory of electrolysis; comprising the absolute evaluation of the E.M.F. of galvanic cells, or of that necessary, *e.g.*, to decompose water. Kelvin arrived at the conclusion that this was equal to the mechanical equivalent calculated by means of the factor, which Joule determined shortly before, of the heat evolved by the transformations of one electrochemical equivalent, or as he stated it in general terms:—

"The intensity of an electrochemical apparatus is in absolute measure equal to the mechanical equivalent of as much of the chemical action as goes on with a current of unit strength during a unit of time." This simple relation appeared to hold very nearly for Daniell's cell; it gave rise to a great deal of experimental research in the course of the fifties, among which the most important was due to the late Professor Bosscha. The historical importance of this fundamental proposition in electrochemistry is scarcely diminished by the fact that Helmholtz in 1882 showed that it only holds for E.M.F.'s independent of temperature, as is nearly the case with Daniell's cell, whereas if the E.M.F. increases (or decreases) on heating, it is greater (or smaller respectively) than the above value by a small additional term, being the product of the absolute temperature and the rate of variation of the E.M.F. per degree." *

Thermoelectric investigations claimed a great part of the early fifties.

* E.M.F. $= W + \theta \frac{dE}{d\theta}$; secondary influences, such as concentration, pressure, magnetisation, etc., being left out of consideration.

To begin with, Carnot's principle was applied to a thermodynamic treatment of a circuit of two metals with their junctions at any temperature. From this it at first seemed as if the thermo-E.M.F. should follow the same law for any couple, which was, of course, at variance with experience. Kelvin at once came to the rather startling conclusion that the effect discovered by Peltier did not suffice to explain the source of energy, but that electric currents must possess the previously undiscovered property of producing different thermal effects when passing from cold to hot or from hot to cold in the same substance, to a degree differing for each metal. Theoretical considerations of a simpler kind also show that the phenomenon of inversion of the thermo-electric E.M.F. at a temperature characteristic of any couple of metals—as discovered by Cumming and studied by Edmond Becquerel—could not exist unless the metals experienced unequal thermal effects from currents passing from cold to hot or inversely. This reversible thermal phenomenon of electric currents in single metals of non-uniform temperature is now known as "the Thomson effect"; it may also be called a convection of heat by electricity in motion, and may be such that either vitreous or resinous electricity carries heat with it.

A very lengthy and elaborate investigation was begun to test these theoretical conclusions, forming part of the Bakerian lecture for 1856. Thermostatic as well as thermometric appliances being at that time very crude, great difficulties were encountered. Yet these were at last overcome, and the thermodynamic theory was fully confirmed by the experimental demonstration that in iron resinous electricity carries heat with it, this being called a negative Thomson effect. It was also shown that in copper the effect is much smaller and positive.

The direct experimental demonstration having thus been given, the simpler method of determining thermoelectric inversions was again reverted to for a number of couples; amongst others the following neutral temperatures were found:—

Silver Gold.	Gold Zinc.	Iron Cadmium.	Iron Silver.	Iron Copper.
—5·7°	71°	162·5°	237°	280° C.

A thermoelectric diagram was also plotted between —30° and +300° C., exhibiting the thermoelectric bearings of a number of metals, and from this the sign and relative amount of the Thomson effect could approximately be deduced as follows:—

Positive: Copper, zinc, silver, cadmium.
Negative: Iron, nickel, palladium, platinum, mercury.

These results were afterwards confirmed and extended by Le Roux, working with improved methods. A number of physicists—*e.g.*, Clausius—felt rather inclined to consider the effect as a secondary one, due to strains in consequence of non-uniform heating. It was therefore very important to test Kelvin's deduction for mercury, this being

of course incapable of any lasting strain. The work was accomplished for several molten metals by Professor F. Braun in 1885. About the same time Professor Haga gave a direct experimental demonstration of the Thomson effect in mercury; and he has since, together with his pupils, largely contributed to our knowledge of this important phenomenon. For pure lead it practically vanishes, at least within the ordinary range of temperature, and this may therefore be considered the standard metal.

Many experiments were also devoted to the effects of strain on thermoelectric qualities. It was found that for iron the direction of the current through the hot junction was—

From unstretched to stretched for temporary longitudinal strain.
From stretched to unstretched for residual longitudinal strain.
From free to pressed for temporary lateral compression.
From pressed to free for residual lateral compression.

Copper, on the other hand, in many respects behaved inversely. Platinum, tin, cadmium, and zinc were also tried. It was concluded that longitudinal strain in iron develops inverse thermoelectric qualities in the axial and lateral directions, thus establishing a sort of crystallic character. Previous experiments by Magnus were also extended, so as to investigate the influence of permanent hardening by axial pressure, torsion, and rapid cooling.

Subsequently the effect of magnetisation was also tried; a longitudinal magnetising helix was easy enough to apply, but the transverse effect had to be found by various ingenious contrivances. For iron then the direction of the current through the hot junction was—

From unmagnetised to longitudinally magnetised.
From transversely magnetised to unmagnetised, and *a fortiori*.
From transversely to longitudinally magnetised iron.

Temporary or residual magnetisation of hard steel gives the same result, whereas longitudinally magnetised nickel behaves in the opposite way.

We now approach a subject of vast practical interest, viz., the specific conductivity of copper. Kelvin, in 1857, drew attention to the enormous variations of this property for different samples of copper, and also to its importance from the shareholder's point of view. It was shown that mechanical ill-treatment, such as drawing, stretching, twisting, stranding, hammering, as well as hardening, tempering, or annealing was of secondary importance. A few years later a number of analyses were made by the well-known chemist A. W. Hofmann, then of the Royal College of Chemistry, and it was shown that 1 per cent. of impurities may diminish the conductivity by, say, 50 per cent. In 1883 Kelvin wondered at the time it took practical men until they thoroughly believed in the reality of those differences, as resulting from laboratory measurements. A branch of manufacture had grown

up in those twenty-six years for producing "conductivity copper," which has since become an article of such immense economical importance. The highest value given at the outset was about 55×10^4 mhos for a centimetre-cube. The "normal copper standard" is 60 at ordinary temperature; the purest copper nowadays gives 65×10^4 at $0°$, about 700 at $-206°$; judging from the experiments of Kamerlingh Onnes, in liquid helium the value would increase without limit near the absolute zero.

Delicate experiments subsequently showed a very slight increase of resistance for iron and copper under longitudinal stress. But the most interesting effect is that of magnetisation. Applied longitudinally to a soft iron wire, it always slightly increased the resistance; steel behaved in the same way, and a residual effect was also observed. An old experiment by Maggi on the relative thermal conductivities of an iron disc in directions across and along that of magnetisation led to a number of trials with square and circular thin discs magnetised in their own plane. These were fitted with lateral potential electrodes in the way now used to show the Hall effect; and if they only had been magnetised at right angles to their plane Kelvin would certainly have discovered that phenomenon, the possibility and importance of which he foresaw. These measurements of a rather delicate differential type all pointed to the conclusion that for iron the resistance increases along, and decreases across, the direction of magnetisation. Nickel, which at that time was difficult to obtain in proper shape, behaved in the same way. These phenomena all belonged to the class of "small effects." At first iron wire only gave 0·03 per cent. Finally the longitudinal increase was found about 0·2 and 0·7 per cent. for iron and nickel respectively, the transverse decrease 0·35 and 0·5 respectively.

The values for iron now appear even too high, whereas for nickel they are rather lower than may be obtained. Very pure nickel, prepared and kindly sent to me by Sir Joseph Swan, showed a relative longitudinal increase of 1·5 per cent. when magnetised to saturation at ordinary temperature, whereas in liquid air it amounted to over 6 per cent. It is interesting to note how the small effect of $\frac{1}{3000}$ detected by Kelvin's careful and minute measurement has gone on enlarging. In my laboratory bismuth was made to increase its resistance in a transverse field of 50 kilogauss (50,000 C.G.S.) to about the four-fold value; in liquid air to more than the hundred-fold value, the latter effect being, however, very variable. Lately a certain kind of non-metallic graphite was found by Mr. D. E. Roberts to acquire more than twenty-fold resistance in such a field at ordinary temperature, and much more at lower temperatures when its crystallic axis was parallel to the field. The longitudinal effect is considerably smaller.

This long series of resistance measurements led Kelvin to devise proper methods; he improved Wheatstone's device and constructed the low-resistance bridge described at length in 1861. His continuous contact rheostat has also grown out of an appliance of Wheatstone's, and is useful in many ways. From the outset Kelvin had, of course,

to face the fundamental question of units, and of the dimensions first used by his favourite author, Fourier. He never belonged to the class of mathematicians who feed us on formulæ containing abstract quantities, complex, transcendental, diverging, or otherwise incapable of actual computation. The consistent system of absolute measurement in terrestrial magnetism, due to Gauss, had been extended to every department of electrical science, chiefly by Wilhelm Weber, the practical value of whose work Kelvin greatly appreciated. As early as 1851 we find a paper on the applications of mechanical effect to the measurement of E.M.F. and resistance in absolute units; in modern language it simply proves that the code address of this Institution may be equivalently abbreviated into the name of James Watt; and as late as 1888 we find Kelvin collaborating with Professors Ayrton and Perry to add another measurement of v to the long list of determinations of that most important quantity. A potential was measured electromagnetically with a centi-ampere balance, and electrostatically with a specially designed absolute electrometer; a known resistance and a "multiplying condenser" were also used. The corrected result was $v = 300{,}400$ km. per second, in good agreement with the velocity of light; it retains its fundamental and universal character even in the modern four-dimensional world of relativity.

Kelvin was the moving spirit of the B.A. Committee on Electrical Standards, which did so much preparatory work during twenty years from 1862 onward. He was also the most prominent delegate at the first International Congress, held at Paris in September, 1881, within the Electrical Exhibition. To this we owe the definite sanction and ultimate legalisation of the volt, ohm, ampere, coulomb, and farad, several questions of detail being settled at an adjourned conference in the next year. Kelvin gave a summary of this important subject before the Institution of Civil Engineers on 3rd May, 1883, being the last of a series of lectures on the practical applications of electricity. In this somewhat bewildering flight of imagination he uttered the well-known dictum that "The life and soul of science is its practical application."

III.

Magnetism was also early taken in hand by Kelvin. He showed that a complete mathematical theory could be founded on known facts, while the results quite agreed with those previously deduced by Poisson on a highly improbable hypothetic base. Even the initial definitions are remarkable for their originality; the conception of a magnetic axis, the ideas of magnetic strength, moment, intensity, and direction of magnetisation being propounded in a clear physical style, strongly contrasting with the mere analytical symbols the pure mathematicians used to deal with.

A demonstration was given of how to represent the action of any magnet by matter distributed on its surface and in very exceptional cases through its interior; but the conventionality of bringing in such

purely imaginary matter was strongly insisted upon as very artificial, though often convenient. In every case the demonstrations tend to exhibit the physical principles expressed in the analytical formulæ. The conception of potential, first introduced by Green in 1828, and independently by Gauss, is freely made use of.

The analytical expressions for various distributions had been frequently dealt with, and Laplace's or Poisson's equation was well known. Kelvin did not rest content with this, but sought clear geometrical illustrations connected with names easy to grasp. As a matter of fact, all this applies to each vector distribution, whether magnetic, electric, or otherwise, and remains, to my mind, of great advantage in expounding these fundamental conceptions. Kelvin in 1850 used Cartesian co-ordinates, and would never give up the tools which served him so well in his youth. We must now admit the fact that vector-analysis has won the field, also on the Continent; though it may seem perplexing to the student that almost every teacher who respects himself deems it necessary to use his own adaptation of the original quaternions, with special nomenclature and symbols.

Quite apart from the analytical mode of exposition, Kelvin's illustrations retain their value. Any distribution may be called complex-solenoidal. A simply solenoidal distribution possesses no sources or sinks, or in vectoral language its *div*(...ergence) everywhere vanishes; it must satisfy the hydrodynamic conditions of continuity in space and at boundaries. Whereas a simply lamellar distribution has a potential, from which the vector is derived, the vector-lines possessing a system of orthogonal surfaces. In hydrodynamics this corresponds to the absence of vortices; that is to say, the *rot*(...ation) vanishes all through. In lecturing Lord Kelvin used to emphasise the two "r's" of such an irrotational distribution with truly Scotch ardour, inimitable by Southern articulators. In a complex lamellar field the orthogonal surfaces still occur, but they are no longer equipotential.

To return to magnetism in particular. Its well-known three vectors, B, H, I, are representatives of each of these distributive types. Faraday's wonderful intuition taught him to think of the induction B as essentially solenoidal. The vector H, on the other hand, is lamellar, except inside conductors conveying a current. The induced magnetisation I may be shown to have nothing in general but a merely complex lamellar distribution, whereas, according to Poisson, it ought to be both lamellar and solenoidal. On 21st December, 1887, Lord Kelvin wrote to me: "As to the potential of magnetisation, I think that word was unfortunate, because in practical cases the magnetisation does not fulfil the potential law." However, in the majority of cases it remains solenoidal. It is only quite recently that I have found an apparent departure from this in the pole-pieces of my half-ring electromagnets, shaped so as to give 50 kilogauss; but they actually produce 55, and this very welcome addition to the calculated value can hardly be explained by other causes than sources and sinks inside the cast steel—an effect constituting what I have called "supersaturation." The somewhat

abstruse theory of vector-distribution thus leads to a very tangible and useful practical result.

Ampère's experiments were considered by Kelvin as the foundation and his conclusions as the elements of the mathematical theory of electromagnetism. He worked out the properties of linear currents, current sheets, and current-conveying conductors at length, and discussed the equivalence of closed circuits with magnetic shells. As a matter of fact, the electromagnetic action of an infinitely small plane closed circuit is shown to be the same as that of an infinitely small magnet perpendicular to such plane. Hence Ampère's orthodox hypothesis of everlasting molecular currents to explain magnetism. The physical reality of this, however, Kelvin did not admit; certainly not in the original form. In fact, he considers it absolutely impossible to conceive of such currents round the molecules as having a physical existence. In a tentative paper of July, 1899, certain speculations on magnetism and molecular rotation were set forth bearing upon this subject. Moreover, W. Weber had already shown that rotating electric particles may take the place of the currents, and Professors Richarz and Chattock have long ago worked out the idea for rotating ionic charges, or, as we would now say, electrons.

Nobody doubts of the explanation of magnetism by pre-existing elementary magnets capable of being directed. The second Kelvin lecturer's beautiful theory is too well known to need further elucidation. For brevity, let us call our elements magnecules, which implies no specification of their ultimate electro-mechanism or chemical structure. Now, Kelvin always thought the theory of magnetism must be essentially kinetic. It always struck me when admiring Sir Alfred Ewing's models that the two-dimensional swinging of his small needles comes to rest very soon. Not so the motion of the actual magnecules in space, which deserves a closer study; I have consequently worked out their three-dimensional dynamics about ten years ago. In doing so I could explain diamagnetism and actually make diamagnets of more than sufficient strength; in fact, negative permeability and self-induction appear attainable by their help, though, of course, this case never occurs naturally. For paramagnetism Curie's rule comes out by simple "magnetokinetic" considerations and by applying the Maxwell-Boltzmann law in connection with the question of kinetic stability I believe I gained some ground in the understanding of hysteresis and ferromagnetism, the main feature of which remains intermagnecular action.

The magnetic potential of a closed electric circuit is expressible in terms of the solid angle subtended by it. This problem thus comes to be a case of spherical projection; and Kelvin actually illustrated it with diagrams obtained by tracing the shadow of a helical circuit produced by a luminous point placed in different positions relatively to it. In connection with this the "mechanical value," *i.e.*, potential energy, of magnetic distributions was calculated. Incidentally, general propositions were deduced for geometrically similar rigid magnets and systems of conductors, from which by combination the following rule

may be deduced: "Geometrically similar electromagnets bearing currents proportional to the linear dimensions show magnetisations equal in value and direction at corresponding points." I have always found this most useful in practically designing electromagnetic appliances on various scales, especially so for the three sizes in which my half-ring electromagnets for obtaining strong fields are now made. The rule at once explains why ampere-turns are more easily placed on larger than on smaller electromagnets, and consequently the coils occupy relatively more space on the latter.

Several inverse problems were treated in which, the field being given, it is required to find distributions of magnetisation or of electric currents by which it can be produced. This theory was at once applied to find a system of earth currents capable of producing wholly or in part the earth's magnetic field and its observed variations. The influence of atmospheric or external sources of magnetism as well as of a ferromagnetic terrestrial core are expressely excluded, though it seems very probable now that these have more or less to do with the real phenomena. In his presidential address to the Royal Society* Kelvin considers a direct magnetic action of the sun "not absolutely inconceivable," but it must be a magnet of 12,000 times the average intensity of the terrestrial magnet. This remark appears to me very important in connection with the solar fields of 3 to 4 kilogauss, *i.e.*, 20,000 times the earth's mean horizontal field, which Professor Hale has lately found by his method of the Zeeman effect.

In his mathematical theory of induction, Poisson had not overlooked the possibility of magne-crystallic actions; and after their discovery by Plücker and Faraday, Kelvin set to work to establish a complete theory upon a purely experimental foundation. He starts from two "Laws of Magnetic Induction." (1) A given body becomes magnetised in a manner dependent solely on the field which it is made to occupy; hysteresis is thereby excluded. (2) The distribution of induced magnetism is the resultant of all the different partial distributions.

This principle asserts the mutual independence of superimposed distributions, thereby implying proportionality of I and H. The behaviour of spheres in the field is then considered. It is remarked that the direction of I may not in general be the same as that of the field, thus preventing the sphere's equilibrium, except in particular positions; most subsequent magne-crystallic methods start from this idea. Poisson had already deduced the general relation between I and H; it is one of the first instances of the numerous linear vector functions, as we now call them. Kelvin reduced the nine coefficients to six by the conservation of energy, and then to three by properly choosing his three rectangular axes relatively to the crystal. These he subsequently called the principal susceptibilities, thereby introducing this very useful term. They reduce to two for uniaxial crystals, and to one for ordinary cubic crystals or isotropic substances.

* *Proceedings of the Royal Society*, vol. 52, p. 304, 1892–3.

The theory was, from the outset, in general accordance with known facts. Careful quantitative tests with spheres of quartz and calcspar were made by Stenger and Walter König, which fully confirmed Kelvin's mathematics. The differences between the principal susceptibilities were observed to be of the order of 10 per cent., for bismuth something near 30 per cent. Professor Morris Owen, while lately working in my laboratory, found diamagnetic graphite from Ceylon to have a principal susceptibility along the axis numerically five-fold the value for directions at right angles to it. We may thus say it has a "magnetic plane" of minimum diamagnetism.

Kelvin expressly excludes from his theory steel, soft iron, nickel, and "the substances of which magnets are composed"; and he knew very well what he was doing, when asking Faraday to experiment upon crystals of iron ore in a letter dated 24th July, 1849. The researches of Professor Weiss on natural cubic crystals of magnetite have shown that this substance behaves æolotropically, somewhat like cubic crystals were known to do as regards their elastic properties. Kelvin's theory was more or less amended for such cases by Professor Voigt and others; but its character of physical simplicity was thereby somewhat impaired. Uniaxial ferromagnetic crystals have also been investigated, *e.g.*, hæmatite, ilmenite, pyrrhotine; they all have a so-called "magnetic plane," the interesting properties of which Professor Weiss has investigated at length for the latter mineral.

When Kelvin started this work about 1850 the magnetic saturation of iron only began to be suspected from certain experiments by Gartenhauser, J. Müller, and Joule. And even much later (1872) the only absolute measurement of susceptibility made was that of Thalén for iron—giving 45, or 566 for the permeability—and hope was expressed that before long experimenters would take up the subject. They have certainly done this with great vigour; so that the amount of data is now overwhelming and may be said to constitute a new chapter, viz., the magnetic properties of matter, alias magneto-chemistry in which great advance has lately been made, chiefly on the Continent. Even in 1900 this subject was sufficiently advanced to enable my reporting on it to the first International Physical Congress in Paris. I dwelt upon the ferromagnetic properties of the four metals, Mn, Fe, Co, Ni, in the initial, intermediate, and final stage, and the influence of temperature below and above the point of transition; amalgams, alloys, and compounds—natural or artificial—were fully discussed, so far as they were then known. Some of them form a continuous transition to the paramagnetic class, which was next described; I proposed "Curie's law" and "Curie's constant" as names in connection with the thermomagnetic researches of that lamented pioneer, and these have since been generally adopted. In the diamagnetic class the data for inorganic and organic substances and for crystals were summarised. I finally mentioned my experiments on certain animalcula—rotatoria, infusoria, and the like—subjected to a field of 50 kilogauss in a wet chamber. Not the slightest effect on their movements was ever observed with

this "micromagnetic" apparatus; as Kelvin once expressed it: the absence of a perceptible magnetic sense is a marvel.

Diamagnetic and paramagnetic substances are now amenable to measurement with reasonable accuracy, and the pernicious influence of millionths of ubiquitous ferric admixtures may be properly eliminated in sufficiently strong fields. It is interesting to note that Kelvin proposed a good method for such work at the B.A. meeting in 1890. In my laboratory Professors Kōtarō Honda and Morris Owen have since been studying the elements within a temperature range from $-200°$ to $+1,300°$ C. There is no evidence for assuming a variation of their real specific susceptibility with the field; its value at ordinary temperature ranges from -15 (maximum for graphite and ten times the value for bismuth) to $+100$ millionths for oxygen. Plotted in terms of the atomic weight, it shows a more or less periodic curve; its connection with allotropy is very striking; one element—viz., tin—may exist in a diamagnetic (grey tin) variety as well as in the usual paramagnetic white form. Temperatures of transition or melting-points often correspond to discontinuities in the diamagnetic susceptibility. Otherwise the influence of temperature presents many aspects; eight diamagnetic elements remain unchanged throughout. This is by no means a general property, as was of late wrongly assumed by several French investigators.

In 1899 I had the good fortune to find that the compounds of so-called rare earths are strongly paramagnetic—more so than those of the iron series—and that this property afforded a quantitative test: a mode of proceeding now adopted by Professor Urbain in his chemical work on these interesting substances.

The metals cerium, praseodymium, neodymium, and erbium, were recently tested; their specific susceptibility is a fraction of that for oxygen, and, like this, it is approximately inversely proportional to the absolute temperature within a more or less extensive range, thus roughly satisfying Curie's law, which has also long been known to hold for many paramagnetic salts, either dry or in solution, and is essentially a "limit law," as I considered it from the outset.

It is worthy of remark that in 1856 Kelvin had proposed to investigate the temperature variations of susceptibility and magne-crystallic effects, which he once called magnetodynamic properties.

A good deal of work has already been done in organic magneto-chemistry, concerning the diamagnetic properties of many series of hydrocarbons, alcohols, acids, and the like. Lately interesting cryo-magnetic work at temperatures down to that of liquid helium has been done by Professor Kamerlingh Onnes and several Dutch and foreign collaborators in the Leyden laboratory.

As regards ferromagnetic matter, it is impossible to draw a sharp line between it and paramagnetic substances. On the whole we may, however, say that it exhibits saturation and hysteresis; it has a temperature of transition, and in many cases shows Kerr's magneto-optic effect to a measurable degree. The amount of information concerning

iron in its various states and alloys, and also nickel and cobalt, is of course enormous, and most of it is so familiar that it seems useless to dwell upon it. It is perhaps of more interest and probably of more importance with regard to the ultimate theory of magnetism, to say something about several less well-known substances of the ferromagnetic class; this now extends far beyond the three metals, the marvellously unique magnetic behaviour of which was emphasised by Kelvin before this Institution (9th January, 1890). The temperatures of transition are added in brackets. Besides the duly crystallised magnetite [555°], hæmatite, ilmenite, pyrrhotine [345°], already referred to; chromite, almandine, augite, franklinite [61°], and a few other minerals used to be called "attractive" by mineralogists.

More than fifty years ago Wöhler prepared the black oxide of chromium [$Cr_5O_9 = CrO_3\ (2Cr_2O_3)$], which, no doubt, exhibits ferromagnetism, losing it at as low a temperature as 102°; according to Shukoff $Cr_4O_9 = 2CrO_3 . Cr_2O_3$ also exists with a transition point of 125°. However, the most interesting metal is manganese; certain varieties of the metal itself have repeatedly been found to show ferromagnetism, losing it at about 450°; it is still somewhat doubtful whether this is attributable to the presence of oxides, hydrides or the like; maybe a trivalent allotropic modification also occurs in such varieties.

Drs. Hilpert and Dieckmann have quite lately described the following series of ferromagnetic compounds of manganese with elements of the fifth group :—

Phosphide, MnP [18–25°]	Antimonide, $MnSb$ [310–320°]
Arsenide, $MnAs$ [45–50°]	Bismuthide, $MnBi$ [360–380°].

Other ferromagnetic compounds of manganese with metalloids have been studied chiefly by Professor Wedekind, *e.g.*, the monoboride MnB [450°], sulphide, selenide, telluride, and nitrides. Tin and manganese combine to form Mn_4Sn, the ferromagnetism of which is interesting with regard to the well-known Heusler metal; but the consideration of anything beyond well-defined compounds, and especially of such ternary alloys of complicated structure, would lead us too far astray.

If one considers the loadstone Fe_3O_4 as a ferroferrite $FeO . Fe_2O_3$, the question arises how "metaferrites" of other metals may behave in which the ferric oxide claims the acid part. Dr. Hilpert systematically prepared such compounds, and found cupriferrite [418°], cobaltoferrite [520°], artificial ferroferrite [525°] strongly ferromagnetic. Ferrites of zinc, calcium [156°], and barium also possess this property in a less degree. The carbide, phosphide, and boride of iron appear to be ferromagnetic; also the amalgams of iron and cobalt, investigated very fully by Professor Nagaoka in my laboratory. Here we have also redetermined many of the above transition points. The Kerr effect was investigated by Messrs. Loria and Martin for most of these compounds, generally showing a characteristic dispersion, often also a rotation of opposite sense for light of different colours. Amongst magneto-

optically active substances are crystallised or amorphous Fe_3O_4 (±), $CuO . Fe_2O_3$ (±), Fe_3C (—), Fe_7S_8 (±), *i.e.*, pyrrhotine, in the direction of the axis of easiest magnetisation, MnSb (—), MnBi (+), Mn_4Sn (—), the sign referring to the sense of rotation. On the other hand, the magnetic Heusler alloy shows no Kerr-effect, while non-magnetic nickel-steels and manganese-steel do so, as I showed in 1890, when I first applied to the latter the method of corrosive etching, now so much employed in metallography. All this tends to show that magneto-chemistry may claim some advance since 1872, and furnishes us most valuable substances. The very full discussion on this subject at the Faraday Society's meeting on 23rd April may be referred to as an instance.*

According to Faraday's researches on diamagnetism all the phenomena resolve themselves into this: that a portion of such matter tends to move from stronger to weaker places of the magnetic field. Kelvin proceeded in 1847 to illustrate these effects mathematically by first calculating the mechanical forces experienced by small spheres in the field; he found these to be directed down or up the gradient of the square of the field for diamagnetic or paramagnetic spheres respectively; the stability of the equilibrium was carefully investigated theoretically and also tested by a number of ingenious experiments. The equilibria and the oscillations of elongated bodies, *e.g.*, rows of balls or cubes, bars, needles, or cylinders in uniform and variable fields were also fully discussed. These considerations once for all set right all the ancient observations on attraction and repulsion, including a number of apparent paradoxes; in the fifties these questions of diamagnetic polarity and the like had given rise to a lively exchange of letters between Tyndall and Kelvin. We may now say that the latter's views survive to the present day and form the base of all methods used in such researches, the results of which have been mentioned above. This theory also throws much light on Faraday's ideas on magnetic fields and lines of force. During my stay in Glasgow much work was spent on applying such effects to ampere gauges and even to current standards. Iron plungers of infinitely varied forms were sucked into coils of varying pitch or into variously shaped conductors, and the distribution of H, H^2, and of the force studied in detail; short iron pistons, balls, oblates or cubes, were found to answer well, their hysteresis proving negligible. About the same time large numbers of such gauges, designed by the late Professor F. Kohlrausch, were also used on the Continent.

Lord Kelvin repeatedly expressed his opinion that most if not all properties of matter are affected by magnetism, at least in strongly ferromagnetic substances. He spent much work on testing such effects. He devoted much thought and sleepless hours also to the first magneto-optic effect discovered by Faraday as well as to those found by Kerr and Kundt. In 1856 he argued that the natural non-magnetic helicoidal property shown by sugar, turpentine, quartz, etc., is

* *Transactions of the Faraday Society*, vol. 8, No. 1, 1912.

due to a right- or left-handed symmetry in the constituent molecules; this idea was extended by Pasteur, thus giving rise to van't Hoff's and le Bel's asymmetric carbon atom and, indirectly, to stereochemistry. But he used to insist upon the fundamental difference between this and the magnetic rotational effect of an essentially dipolar nature. This discussion brought him remarkably near considerations now familiar in connection with Professor Zeeman's discovery of the influence of magnetism on the lines of emission and absorption spectra of metallic vapours, and with the foundation of the electronic theory by Professor Lorentz. In collaboration with Dr. Elias I have recently shown that compounds of the chief paramagnetic series of elements exhibit strong selective absorption-lines, for most of which the Zeeman effect is a very marked feature when subjected to strong fields at liquid-air temperature; natural or artificial ruby—owing its beautiful colour to oxide of chromium—is the most striking example of a crystal showing a strong Zeeman-effect for two red lines of fluorescence or absorption. Salts of the rare earths are also very interesting in this respect; some of the natural minerals containing them were studied by Mr. Jean Becquerel. The Faraday effect shows enormous anomalies near the absorption bands and transverse double refraction was also found in certain cases.

The effects of stress on the magnetisation of iron, cobalt and nickel were studied by Kelvin in the seventies. He had been anticipated by Villari (1868) in the most remarkable of his results, viz., the increase or diminution of magnetisation of soft iron by longitudinal pull, according as the magnetising force is less than, or greater than, a critical value of about 10 gauss. Transverse pull showed correspondingly opposite effects with a critical field of about 25 gauss. G. Wiedemann's researches on the relation between torsion and magnetism were also repeated and extended. The results were plotted in curves, which show a remarkable lagging of effect or residue of influence of previous conditions—*i.e.*, hysteresis; cobalt and nickel show opposite effects; the critical field for the latter was found to be about 250 gauss. The longitudinal currents in iron and nickel wires induced by twist when under longitudinal magnetisation form the subject of a note in 1890.

IV.

Electromagnetic machinery continually claimed Lord Kelvin's attention; in 1872 he published a paper on "The Dynamical Value of Electromagnets," in which we find the well-known $B^2/8\pi$ formula for electromagnetic stress. That expression is recommended as very useful in the theory of such machines. Though this problem has been more fully considered by Clerk Maxwell, the above formula is sufficient for practical purposes. Professor Taylor Jones, working with me in 1895, has carefully confirmed it within a wide range by two experimental methods. The strongest field in air measured by us was about 75 kilogauss, which might easily be further increased to-day. It

corresponds to a stress of 225 kg.-weight per cm.^{2}, or rather more than the tensile strength of lead. Kelvin was always much impressed by these enormous strains, and expressed his wonder at them at a meeting of this Institution. He also refers to them in a paper "On the Duties of Ether for Electricity and Magnetism" (1900), concluding that it is not for want of strength that we need question the competency of ether to transmit magnetic force. The magnetic balance formerly designed by me is wholly based on the validity of the stress formula and in consequence its scale is quadratically divided. In its modern form it has been used in several of the investigations on magnetic properties of matter alluded to, as well as for tests of material used in practice.

A note on the induced magnetism in a plate (1845) contains the theory of magnetic images by multiple reflection in a plane shield. It is shown that an infinite series of images, of strength diminishing in geometrical progression has to be considered. Professor Weiss has lately applied this principle in his improvement of the second Kelvin lecturer's fertile isthmus method. Kelvin published a paper on electric and magnetic screening in 1891, in which five kinds of screening were distinguished, including window-shutters, as well as variational screening against E.M.F. and M.M.F. As regards magnetostatic shielding, it is well known that since 1858 he protected his marine galvanometers by means of a thick cylindrical sheath of iron. Sets of thin concentric hollow cylinders were also tried in the laboratory, but not adopted in practice. When electric tramways began to distress the nerves of physicists, Lord Kelvin, at his jubilee in June, 1896, advised me to try to find my way in that direction. So I set to work on the theory of spherical and cylindrical bi-lamellar and tri-lamellar sheaths, paying due regard to economy of weight. The theory of simple shells was revised and experimentally tested with respect to internal and external shielding and to the determination of initial permeability. Shielded or buried conductors were also investigated with regard to the drag on them and the E.M.F. induced, in consequence of a discussion in which Mr. Mordey had a prominent part. A number of filings pictures served to check the theoretical line-of-force diagram calculated from the formulæ.

The design of multi-lamellar ironclad galvanometers could then be taken in hand. In collaboration with Professor Rubens, I brought out such an instrument, with two spherical and one cylindrical sheath of cast steel, which is now used a good deal in the struggle against stray currents. It reduces the perturbation to less than $\frac{1}{1000}$ or $\frac{1}{2000}$. In some towns this is insufficient, and I therefore aim at a shielding ratio of $\frac{1}{10000}$, which may be obtained by taking 4 or 5 shields, or, better still, by improving the initial permeability. Metallurgists unhappily respond rather more slowly to the demand for a good material with, say, $\mu_0 = 500$ or more, for such harmless galvanic dreadnoughts than they do for the sheathing of their less peaceful namesakes of 50,000 tons. In all other respects these instruments are mainly designed on the lines laid down by Kelvin for galvanometer construction.

The idea of hydrokinetic analogies in magnetism was first enunciated by Euler (1761) in his letters to a German princess, and was very fully worked out by Kelvin. He has repeatedly dwelt upon the complete formal similarity between the mathematical theories of magnetic induction, dielectric polarisation, and of Fourier's theory of thermal conductivity on the one hand, and the theory of certain hydrokinetic processes on the other. Diffusion in solutions and electric conduction may, moreover, be added. A porous solid of fine-grained texture was assumed, through which filters an incompressible frictionless liquid. The ratio of the flow to the kinetic energy per unit volume is called the hydrokinetic permeability, and this expression may then be generalised. This analogy is illustrated by numerous special problems with full calculations and diagrams. For example, the flow through a sphere of permeability $\frac{1}{2}$ was depicted corresponding to a diamagnetic sphere of the same value.

In 1872 the general problem of magnetic induction was subjected to an exact mathematical treatment with due regard to those analogies. I have always attempted to lay stress on the fundamental importance of these researches in the modern theory of the magnetic circuit; in fact, correct interpretation of mathematical results was only needful to apply them at once to practical problems. My theoretical investigation of the normal test-case, viz., the radially divided toroid, or split-ring, was sufficiently confirmed by H. Lehmann's experiments in 1893. It showed that the ancient orthodox potential methods lead to the same result as those in which the induction claims an important part; there is really no essential discrepancy between the two modes of viewing such questions. Every one is, of course, aware that John Hopkinson played a prominent part in introducing those exceedingly important conceptions into the domain of engineering. They form a tribute to his memory as well as to that of Lord Kelvin, who, in this Institution's meeting on 10th January, 1890, expressed his high appreciation of Hopkinson's person and work.

The theory of electromagnetic induction, founded on the elementary experiments of Faraday and Lenz, had been subjected to mathematical analysis by Franz Neumann, and a theorem was demonstrated, completely expressing the circumstances which determine the induced current. In 1848 it appeared to Kelvin that a very simple *a priori* demonstration might be founded on the "equivalence of mechanic effects," *i.e.*, the conservation of energy, and consequently he deduced Neumann's equation from this principle, unaware of the fact that Helmholtz had anticipated him the year before. He did not meet the famous German physicist—who became one of his best friends—until 1855, thus "making his acquaintance, which he had been anxious to do ever since he first had the 'Erhaltung der Kraft' in his hands."

In this classical work Helmholtz had suggested as a conjecture that the discharge of a battery is not always a simple motion of electricity in one direction, but one backward and forward between the coatings in oscillations which become continually smaller until the entire *vis viva*

is destroyed. The experiments of Riess and Feddersen on the magnetisation of fine steel needles by discharges, as well as multiple flashes of lightning, were, according to Kelvin, due to their oscillatory character. His analysis had pointed out that this must occur when the resistance is smaller than double the square root of electrodynamic over electrostatic capacity; for the numerator we would, of course, say self-inductance. These few pages of integration thus contain in a nutshell the possibilities of the electromagnetic theory of light, Hertzian waves, and wireless telegraphy.

Occasional papers on electrification and diselectrification of air by flame, bubbling through liquids or contact with electrified steam give evidence of Kelvin's interest in such questions of ionisation. The discoveries of Professor Röntgen, Henri Becquerel, and the Curies profoundly impressed him and gave rise, during the last decade of his life, to a series of notes on radioactivity and electrions, as he used to call them, collected in the last volume of his papers.

Lord Armstrong once had his hand severely burnt and blistered in short-circuiting a dynamo through a steel bar. Kelvin rather epigrammatically called this a wonderful incident and an accidental experiment, illustrating the fundamental principles of electromagnetic induction, and forthwith went for the mathematical solution. He was thus led to an approximate calculation of the skin-effect, showing that in such cases there may be amply sufficient current through an exceedingly thin outer shell to produce very suddenly a high surface-temperature without sensibly heating the ineffective copper forming the body of the conductor. He reverted to this question and showed that in certain cases copper may even be anti-effective. For completeness' sake, a series of papers ought to be mentioned on the velocity of electricity, on peristaltic induction, on discharges of cables and the like, containing the fundamental points in submarine long-distance telegraphy, so clearly and fully set forth by the second Kelvin lecturer.

In the Glasgow Laboratory a stretched wire in a magnetic field was a favourite device for measuring the field or the current, either being expressed in terms of the other. The function of the two strings in Sir Alfred Ewing's magnetic curve-tracer is well known. Professor Cotton's field-measuring instrument and the string galvanometer of Professor Einthoven represent the latest developments of this idea.

The same principle is applied in a modified form in the syphon recorder of 1870, constituting the first moving-coil instrument. There can be no doubt that this is a "Thomson galvanometer" just as well as the earlier mirror galvanometer of 1858, with its concave magnet-mirror of small inertia, controlling magnets, and damping arrangement. But if we were to do justice to his overwhelming fertility, we would lose our way amongst the multitude of "Thomson effects," Kelvin theorems, and the like. We may almost regret that William Thomson, Baron Kelvin of Netherhall, Largs, had no more names to label his discoveries, however, not "to bury his illustrious identity," as

Taine expressed it. So the crumbs from the rich man's table sometimes sail under the flag of whoever stoops to pick them up.

The Paris electrical exhibition of 1881, and its successor in Vienna two years later, are milestones pointing to a period of immense activity in the adaptation of heavy currents to the everyday uses of mankind. It has been my good fortune to attend Kelvin's laboratory during the bustle of those days, entirely differing from the well-directed aims of the students under a modern organisation for teaching or research. Yet none of the pupils in after-life would have wished to miss that unique experience, though it may not have been the shortest road to acquire learning or degrees. Kelvin kept continually moving about between his house, the laboratory, and "White's," besides many other places in the United Kingdom and abroad; many of his instructions were mailed or wired or cabled, often a rather distressing mode of shaping the raw student. It was a time of reaction against the Faure accumulator, received with the utmost enthusiasm, and afterwards too forcibly discarded because, in its undeveloped form, it could not perform what it promised; primary batteries of all sorts for current or potential or standardising were continually being tried.

Kelvin's improvements in the heavier kind of electric machinery are of secondary importance; but his immense labour on instruments, standards, gauges, and meters has done much towards improving this type of apparatus, and a good deal of it survives. Of all the designs of the eighties, I believe we may say the measuring instruments have proved fittest. I hope I am not betraying secrets in stating from my notebook that on 15th February, 1884, the first "current-standard" No. 0 was put into my hands for a preliminary test; a movable flat spiral coil was vertically suspended on knife-edges between two larger ones; the current, up to a range of 30 amperes, being led through mercury cups. In November—after the B.A. meeting in Montreal and the memorable Baltimore Lectures—Standard No. 3 came into the laboratory; in this the single set of coils was already horizontal, and currents up to 10 amperes could be measured to ¼ per cent., though the mercury contacts gave trouble. These were superseded by the flat wire ligaments, and the parts were also duplicated in order to annul local disturbances. In this form the standard electric balances were shown to this Institution on 24th May, 1888, and are being manufactured to this day.

The graded potential and current galvanometers were the direct outcome of the old tangent instruments; though they are now historical they did good work and are still useful now and then. I remember having spent much work on conductivity instruments, such as the "gridiron mhometer," using rather too much current, and the "copper mho-ohmmeter." The divisions of this could be made to correspond to a mho, a hectamho, or any such value. An instrument of the same kind was also in use as a "lamp-meter" for the forty Swan lamps in Lord Kelvin's house.

This was No. 11 of the professorial mansions forming an annexe to the University on Gilmore Hill, with its beautiful view over the wharves and yards of the Clyde. It was the first house in Scotland electrically equipped in the winter of 1882. The Dugald Clerk gas engine of the laboratory was used for house-lighting in the evening. Though generally reliable, it managed to fail when a most distinguished company was assembled. As storage batteries were taboo—at least for some years—the total eclipse ensuing was disastrous. Lord Kelvin used to rush out, followed by his assistants, to look after the matter, and the handling of the greasy machinery in evening dress was somewhat of a *tour de force*. Well, even now, after thirty years, such incidents are not wholly avoidable, and last week one could even witness the sun's breakdown during two seconds.* Terrestrial as well as celestial mechanisms evidently have a limit to their perfection. This case of domestic electrification finally leads us to the general domestic, municipal, and all-round industrial applications of electricity, in which Lord Kelvin has also left his mark from the Portrush electric railway to the Niagara scheme. I might also mention his well-known electro-financial law concerning the cross-section of copper in long-distance transmission, but must leave the adequate treatment of these engineering subjects to a future Kelvin lecturer.

Kelvin's first presidential address comes to the conclusion that "we really know nothing below the surface of this grand subject which constitutes the province of the Institution of Electrical Engineers." We can only regretfully repeat this dictum of 1889.

Many generations of students have passed through Kelvin's lecture-room. The laboratory was not "an agreeable lounge where to meet and talk matters over," but its pupils through daily intercourse with their master deeply felt his unique influence and contributed to spread it over different parts of the world. Besides the British and American physicists educated in the Glasgow Laboratory, it is probably the Polish and the Japanese physical school which have been most influenced through sending many of their men to the University of Glasgow. Its distance, the great contrast between its half-yearly curriculum and those of most Continental universities, are probably among the reasons which prevented a larger influx of students from abroad. In Holland, most of whose shipbuilders have been apprenticed on the Clyde, the reputation of Kelvin was always as great as that of his city, and I have mentioned several of our well-known physicists who worked on his lines. Notwithstanding his friendship with Helmholtz, I believe Kelvin's work has never been quite so much appreciated in Germany as it was from the outset in France and Italy. But this was also the case with Clerk Maxwell until the work of Hertz brought that of his theoretical instigator to the front; and as Maxwell confesses that he learnt whatever he knew from Kelvin, as in fact we all did, this indirectly sets matters right. However this may be, Lord Kelvin was an honorary member of the Elektrotechnischer Verein, who enter-

* Total solar eclipse of 17th April, 1912.

tain most friendly relations with this Institution; that corporation was represented in Westminster Abbey on 23rd December, 1907, and an obituary article was published by me in its Journal. The council of the Verein desire me to express on this occasion the high esteem in which Lord Kelvin's memory is held by its members.

In conclusion, I beg to tender my best thanks to Professor Andrew Gray for the fine collection of Kelvin's apparatus of the older types which he has kindly sent from Glasgow.

I am also much indebted to Messrs. Kelvin and James White, and particularly so to Dr. J. T. Bottomley, and to Mr. F. A. King of their Lewisham branch for the sending and arranging of the latest types of instruments.*

We have heard Lord Kelvin state at the Jubilee Dinner in 1896 that nobody would ever understand how much he was indebted to the never-tiring help of Lady Kelvin, not only privately, but also professionally. As a profession we may, I think, express our great sympathy with the devoted companion of one of our chief glories.

Discussion.

Dr. Silvanus Thompson.

Dr. SILVANUS P. THOMPSON: Mr. President, Ladies and Gentlemen, the honour that falls to me to propose the vote of thanks to the Kelvin Lecturer to-night is one that I appreciate greatly, because I yield to no man, not even to the Second or the Third Kelvin lecturer, in the admiration that I have for the memory of Lord Kelvin.

We are all familiar with the fact that a great artist is able, in the work that he produces, to give us not only a composition which is satisfactory in its largeness of conception, in its decorative effect, in its general construction, in its appositeness to the subject, but he is also able to give us the detail of finish without overloading his composition. There are artists who fail of extreme greatness, who nevertheless can do a good deal, and some of whom can give us the great outlines without the finish, or the decorative effect without the detail; and there are others who are exquisite in detail, but who lose the largeness of the composition. But the great artist is master in all. We have only to think of the great names in art, of Michael Angelo, of Titian, of Raphael, of Turner, to say nothing of living masters, to know that they are great in the whole as well as in the detail. And I venture

* Besides a number of slides the following instruments were exhibited:—

1. Old air condenser.
2. Old multi-cellular voltmeter.
3. New multi-cellular voltmeter (100–300 volts).
4. Trial electrostatic voltmeter.
5. Old electrostatic voltmeter.
6. New electrostatic voltmeter (12,000 volts).
7. Old portable electrometer.
8. Ancient mirror galvanometer.
9. Trial current balance No. 3 with certificate of laboratory test by the lecturer of 6th November, 1884.
10. New centi-ampere balance.

Dr. Silvanus Thompson.

to think that that quality which we see and recognise in a great artist is also a quality that can be seen and recognised in the great—the really great—man of science. He is great not only in the theory, in the grasp of principles, but he is also great in the application and design and in the minute detail. But he does not let the largeness of conception interfere with the grasp of application, or in the usefulness of detail; neither does he let love for detail reduce him to the mere niggling of the man who has no grasp on first principles. Now it struck me, when I was listening to Professor Du Bois, that this was most eminently characteristic of Kelvin. Master of first principles and of mathematics, he yet was also master of the design and application of his subject, and master of minute detail. And surely we have also to recognise that those qualities which made him in that way great, a master in the large as in the small, have shown themselves in his disciple who has held forth to-night upon the subject of Lord Kelvin's work. We recognise in him, even if we did not know him before, a man who has a grasp of first principles, who does not despise their practical application, and who is himself a worker in minute detail.

Let us think for a moment of one of Kelvin's achievements, to which the lecturer drew our attention. Not only his mathematical grasp of first principles, but his absolute love for searching down to small effects, show themselves when he was thinking about the conductivity of copper—which may seem a small matter after the great mathematical triumphs of the theory of potential in which he was known all over the world of science—and worrying himself about the effects of fractions of 1 per cent. in the conductivity. And yet we know how fruitful that work has been, and how much we owe to that minute research on the conductivity of copper. Professor Du Bois has had here in front of him one of the instruments on which be worked in the year 1884 in the master's laboratory; and he has told us how, in that year, they had got to an accuracy of one-fourth of 1 per cent. That was the year in which the British Association Meeting was held in Montreal, and there Lord Kelvin gave an exceedingly interesting address about the sources of power. It was the autumn of that year in which also he gave those ever-memorable Baltimore lectures. I remember very well being in Montreal at the time of that meeting. One afternoon there was a reception held in a skating rink, and I was walking round the arena of that skating rink with Lord Kelvin, talking with him about instruments for electric lighting, when he pulled out his pocket-book and showed me a cablegram that he had received from his laboratory in Glasgow the evening before to inform him that the latest kind of current-measuring instrument was now accurate to within one-fifth of 1 per cent. "But," he said, "I am not satisfied; I shall not be satisfied until my instruments are correct to within one-tenth of 1 per cent."

Professor Du Bois has perhaps made some of us think there is a new science growing up. Not many of us have heard, at any rate under

Dr. Silvanus Thompson.

that name, of the science of Magneto-chemistry; but I recommend all who think there is something here to be learned to refer to that remarkable report which Professor Du Bois drew up for the Physics Congress at Paris in 1900, where there is set forth in detail a great deal of his own work, which he has all too briefly spoken of to-night, on the magnetic properties of chemical compounds. Professor Du Bois has done remarkable work; he has been much too modest over his own share in it. He has spoken to us of his semicircular magnets; he has described to us his multiple-shielded galvanometers, his special "ironclads"; and he has suggested to us the "magnecules," which he regards, I suppose, as constituting the foundation of magnetic properties. He has mentioned some very remarkable things: the new result concerning the diamagnetism of crystalline graphite, and the singular observation of the apparent existence of sources and sinks of magnetism inside the steel or the iron of his magnets—a very surprising observation indeed. All these things show that Professor Du Bois is a pioneer, that he has learned his lesson from Kelvin well, and that he is not, as no man should be, ashamed to acknowledge himself a disciple of that great man. We are all disciples of Lord Kelvin, whether we know it or not; we cannot help it, because the science of electricity and magnetism of to-day cannot be other than what it has become through the genius of Lord Kelvin.

I ask you to give a hearty vote of thanks to the Kelvin lecturer for the addition—the most valuable addition—that he has made to the narratives that now exist of the work of Lord Kelvin.

Sir Alfred Ewing.

Sir Alfred Ewing: Mr. President and Gentlemen, at the beginning of his lecture Dr. Du Bois, pleasantly referring to his predecessors, spoke as if the Kelvin lecturers constituted terms in one of those series which mathematicians love because they are capable of summation, series in which successive terms diminish. I am willing to admit that, as regards numbers 1 and 2, the description is perfectly accurate. But somehow or other the function has now changed its mind, and has become one of those which are not the joy but the despair of the mathematician. Professor Du Bois comes to us to-night from a country with which we find ourselves in rivalry—I trust it always will be friendly rivalry—of many kinds, scientific and other. But he himself is only a sojourner there; he belongs to a nearer neighbour of ours which has set an indelible mark on physics and on chemistry no less than upon political history and upon the history of the fine arts. It is well that we should have, from one so qualified to express it, such an international recognition of the value of the great work that Kelvin did, not only for one land, but for all.

Listening to Dr. Du Bois to-night, when he was speaking of magnetism in relation to crystals, I reflected how all knowledge in its process of evolution out of the chaos of ignorance may be compared to a process of crystallisation. In solution we cannot discern the particles; as soon as they become ordered in the crystal we see them.

Sir Alfred Ewing.

It is so with knowledge; physical facts are undiscerned so long as they remain isolated. When they are connected in their proper relation as part of a science they become recognisable, just as do the particles of the crystal. And if we think of Kelvin's work in this connection we may pursue the analogy by comparing it to that species of crystal growth which is called dendritic, where the crystal sends out many arms in various directions, branching out into unoccupied territory, forming a great skeleton—a skeleton, in this case of knowledge, which leaves much work to be done afterwards in filling in the spaces. It is comparatively simple work, work for lesser men to do: that is the kind of work which has been done in vast amount by the disciples and followers of Kelvin. He sent out many long arms, in some sense occupying, at least breaking, new ground in various fields of knowledge. It has been left for others—and Dr. Du Bois has told us of much of this work to-night—to complete the great crystal structure of which those arms were the skeleton. I would congratulate Dr. Du Bois on many things in his lecture, but perhaps most of all on this—that instead of treating merely historically the branch of Kelvin's work which he has taken up, he has treated it as a foundation, and has shown what has been built upon it by other men. This surely is a departure which will be followed in the future by other Kelvin lecturers. It is a most admirable departure because there was no work so foundational as Kelvin's.

And there is another point in the lecture on which, in seconding this motion, I would congratulate Dr. Du Bois with all my heart. He is able to speak of the work of Kelvin, not simply as a scientific student can speak of it, but as a personal friend, a personal disciple, can speak of it. Among those of us who had the privilege when we were younger men of being brought closely under the direct influence of Kelvin, there will never cease to be profound gratitude for that privilege, for he was a man who inspired not only veneration, not only an intense admiration and enthusiasm—an admiration that was almost a passion—but he inspired also the deepest personal affection. We may congratulate ourselves and the Institution on having had so admirable a lecture from one so entirely competent to give it, not only in virtue of his own brilliant investigations, in which he has followed up the work of Kelvin along certain lines, but also on account of this characteristic, that he, too, was a pupil of the master, that he, too, was one who loved Kelvin.

The President.

The PRESIDENT: I now ask you to pass a very hearty vote of thanks to Dr. Du Bois for his lecture.

The Resolution of thanks was carried with acclamation.

Proceedings of the Five Hundred and Forty-first Ordinary General Meeting of the Institution of Electrical Engineers, held on 2nd May 1912—Dr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting, held on 25th April, 1912, were taken as read, and confirmed.

Messrs. J. T. Morris and J. T. Pember were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Members.

Edmund Lucas Cooper.
Alfred Ernest Green.
Adolf Harry Railing.
Johannes Schuil.

As Associate Members.

John Stafford Barker, M.V.O., Captain R.E.
Ernest Gabriel Boissier.
Clifford Oswald Brettelle.
Malcolm Archibald Bulloch.
Noel Kingston Bunn.
Henry Coates.
James Goodchild.
John Herman Gyles.
Wilfrid Thomas R. Jennings.
Walter Talbot Kerr.
Thomas Leeman.
John O. Nichol.
Harry Nutton.
Robert Francis Pitcairn.
George Launcelot L. Russell.
Robert Harry Schofield.
William Brown Simpson.
George Herbert Stevenson.
Harry Holton Stratton.
William Whitney.

As Associates.

Herbert Edwin Blain.
Frederick Henley Ousey.

As Students.

Walter David Chalmers.
William Greenbank Coates.
Harry Midgley.
Mahmud Hamed Mahammed.
Jogendra Nath Sen.
Roger Beverley Walker.
Theodore L. Wenger.

Donations to the *Library* were announced as having been received since the last meeting from G. Allen & Co., Ltd., R. Atkinson (London), Ltd., J. & A. Churchill, Curtis Gardner & Co., Ltd., K. Hedges, Svenska Teknologforening, and Professor E. Wilson; to the *Museum* from K. Hedges; to the *Building Fund* from F. Gill, A. P. Hutchinson, and Professor J. T. Morris; and to the *Benevolent Fund* from J. F. Avila, F. Gill, W. H. Patchell, P. R. Rice, R. M. Sayers, and S. Sharp, to whom the thanks of the meeting were duly accorded.

The evening was occupied in an adjourned discussion on "The Causes preventing the more General Use of Electricity for Domestic Purposes."

Proceedings of the Five Hundred and Forty-Second Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, 9th May, 1912—Dr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting, held on 2nd May, 1912, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

Dr. John Henderson.	Fred V. L. Mathias.
Archibald V. Mason.	Robert C. Pierce.

Francis C. Raphael.

From the class of Associates to that of Members :—

John Geo. Bruce.	George Morrison.

From the class of Associates to that of Associate Members :—

Charles F. Gray.	T. H. M. Swinburne.
Denner John Strutt.	James A. Troughton.

From the class of Students to that of Associate Members :—

Alec Hartley.	Roger K. Keer.
Indra K. Kaul.	Duncan J. MacKellar.

Albert Smith.

A paper by Mr. S. W. Melsom, Associate Member, and Mr. W. H. Eastland, entitled "The Behaviour of Direct-current Watt-hour Meters, more especially in Relation to Traction Loads, with Notes on Erection and Testing" (see page 465), and a paper by Professor David Robertson, B.Sc., Associate Member, entitled "Electrical Meters on Variable Loads" (see page 489), was read and discussed.

THE BEHAVIOUR OF DIRECT-CURRENT WATT-HOUR METERS, MORE ESPECIALLY IN RELATION TO TRACTION LOADS, WITH NOTES ON ERECTION AND TESTING.

By S. W. MELSOM, Associate Member, and W. H. EASTLAND.

FROM THE NATIONAL PHYSICAL LABORATORY.

(*Paper received 22nd January, received in final form 10th August, and read before* THE INSTITUTION *9th May*, 1912.)

In view of the questions which are constantly being raised as to the behaviour and accuracy under working conditions of direct-current watt-hour meters of various types, more especially regarding those used for measuring traction and other power loads, the authors have investigated at the National Physical Laboratory a number of these instruments, each of a different type, in order to ascertain, if possible, the source of the differences which undoubtedly often exist between meters of different types when used to measure power in the same circuit.

Some tests were made on two types of meters with a varying load in 1909.* The apparatus used in these tests for integrating the current had to be improvised in the somewhat short time at our disposal, and, although it gave results sufficiently satisfactory for the immediate purpose, it was decided to construct apparatus for a thorough determination of the behaviour of all of the types of meter in general use for power measurement in this country.

The size of meter selected for the tests was for 200 amperes 480 volts. With the exception of the Allgemeine Electricitäts Gesellschaft (a fairly old 500-ampere 480-volt instrument, for the loan of which we have to thank the South Metropolitan Tramways Company), the meters, particulars of which are given below, were kindly lent by the various makers.

* Report of the National Physical Laboratory. 1909.

Particulars of Watt-hour Meters Tested.

Makers.	Type of Meter.
Allgemeine Electricitäts Gesellschaft	Oscillating type.
Aron Meter Company	Short pendulum meter.
British Thomson-Houston ...	Motor type with external (copper) resistance and shielded brake magnets.
Chamberlain and Hookham ...	Shunted mercury motor type.
Everett-Edgcumbe	Shunted motor type with external (Eureka) resistance in pressure circuit.
Evershed and Vignoles	Motor type.
Siemens Bros.	Motor type.

Except where it is otherwise mentioned, the series resistance in the pressure circuit was inside the meter case.

Various points were raised during the progress of the work, with the result that the tests have extended over a period of eight months, during which time the meters have all been subjected to exactly the same conditions. With a view to determining any change in calibration with time, the meters have now, by the kindness of Mr. A. V. Mason, been connected in the traction circuit of the Sutton station of the South Metropolitan Tramways Company, where their behaviour will be noted under ordinary working conditions, observations being taken of the dial readings and also from time to time of their accuracy on steady loads. As, however, it will be at least a year before any very definite information can be obtained the results will be made the subject of a later communication.

Behaviour with Varying Load.—The behaviour of supply meters on varying loads has been investigated at the Physikalisch-Technischen Reichsanstalt by Messrs. Orlich and Günther-Schulze,* the following extract being taken from their paper on the subject.

"Taking—

$K =$ the moment of inertia of the armature.
$A =$ the damping couple for the angle of velocity W_1.
$a =$ the angle in circular measure which the armature turns through in t seconds.
$D =$ the driving couple corresponding to any consumption Q.
$R_0 =$ the constant part of the friction.
$R_1 =$ the part of the friction proportional to the velocity.

"Suppose now that the load, and the turning moment proportional to it, take from time to time values $D\,t$ which may change in any manner.

* *Elektrotechnik und Maschinenbau*, vol. 27, p. 801, 1909

Suppose the load to be turned on at the time $t = 0$, that is to say at this instant $a = 0$, $w = 0$, then the following equation holds—

$$K \frac{d_2 a}{d t^2} + (A + R_1) \frac{d a}{d t} + R_0 = D t \quad . \quad . \quad . \quad . \quad . \quad (7)$$

"If the armature has no inertia, the angle a_0 corresponding to this case satisfies the equation derived from this by putting $K = 0$, that is to say—

$$(A + R_1) \frac{d a o}{d t} + R_0 = D t \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

"The last equation shows that even under constant load and constant armature speed the meter will only give readings proportional to the load if the constant term for the friction R_0 is reduced to zero by approximate means, such as compensating coils. By subtraction we get from equations (7) and (8)—

$$(A + R_1) \frac{d(a_0 - a)}{d t} - K \frac{d^2 a}{d t^2} = 0,$$

or, bearing in mind the initial conditions—

$$(A + R_1) (a_0 - a) = K \frac{d a}{d t}$$

$$a_0 - a = \frac{K}{A + R_1} w t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

"Formula (9) gives at every instant the magnitude of the error due to the inertia of the armature. The error is at every instant proportional to the speed of the armature at that instant. Since at a short time after the current is cut off $w t$ becomes equal to 0, it follows that the error due to the variation of the load from the instant when the circuit is made, up to a short time after the circuit is broken, is zero under all the circumstances in meters of the motor type. This holds good in whatever manner the load may have varied and at whatever value the moment of inertia, the damping and the friction of the armature may be."

Messrs. Orlich and Günther-Schulze made some experiments on different types of small meters with a varying load, taking for each meter a period so regulated that the rotor had time to come to rest between each current impulse, and, presumably, to rise to maximum speed during the current impulse.

In the investigation made by the authors of the present paper, the meters, some of which were very different as regards the time taken to come to rest, were all subjected to the same range of current variation.

For the measurement of the quantity of electricity flowing through the main circuit of the meter a copper voltameter was specially con-

structed to take the full current continuously. This consisted of 12 cathode and 13 anode plates, each plate being 15 cm. square. The current density at 200 amperes was therefore 1 ampere per 27 sq. cm., and in order to ensure that the deposit at this somewhat high-current density was even and homogeneous, the electrolyte was kept agitated, according to a suggestion made by Mr. F. E. Smith, by means of a current of air supplied by a filter pump. The air was passed into a coil of copper tubing laid at the bottom of the voltameter; the end of the tube in the electrolyte was closed and the air allowed to pass into the solution through a number of small holes in the tube. The air

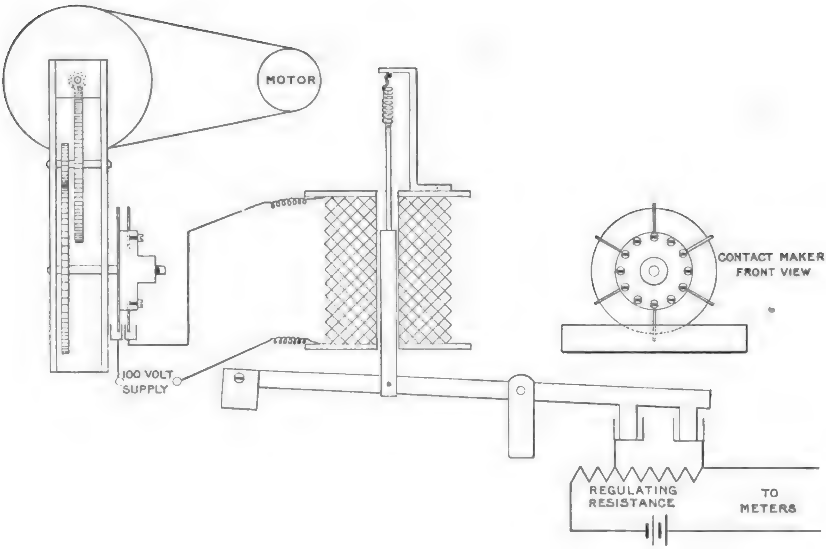


FIG. 1.—Apparatus for varying the Load.

served not only to keep the electrolyte in motion, but also to keep the temperature down, the maximum rise at the end of a 2-hour run being not more than 3° C.

The electrolyte was made up, according to the formula given by Professor Gray, by dissolving commercial $CuSO_4$ in distilled water until a density of from 1·15 to 1·18 was obtained, 1 per cent. of free H_2SO_4 then being added.

In other respects the voltameter was on the same lines as those used by Professor T. Gray* and Mr. A. W. Meikle.† It worked quite smoothly, the only difficulty met with being that fresh acid was required from time to time; failure to renew this resulted in a powdery deposit which it was impossible to collect.

* *Philosophical Magazine*, vol. 22, 5th series, p. 368, 1886.
† *Electrical Engineer*, vol. 1, new series, p. 270, 1888.

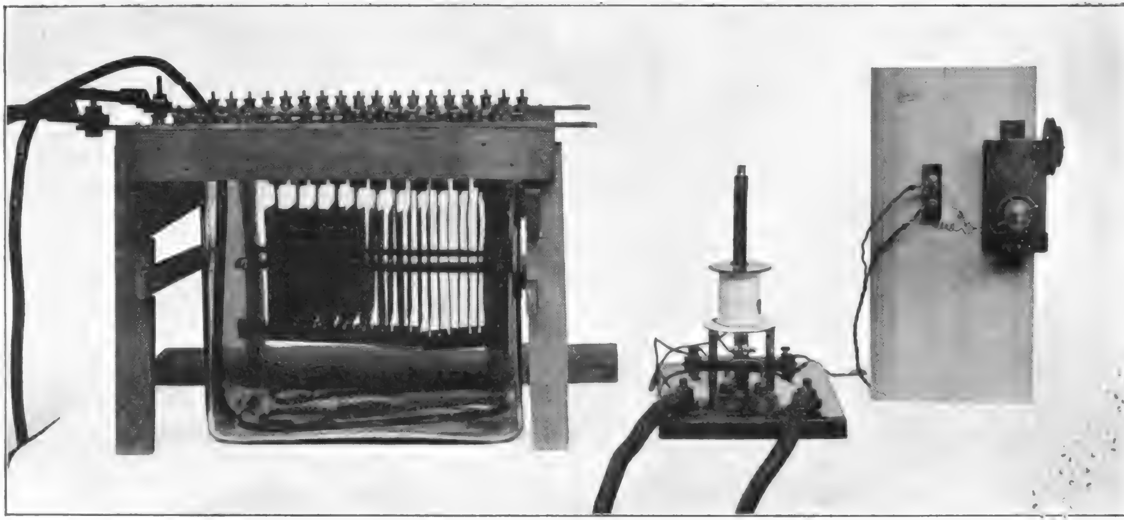


FIG. 2.—Copper Voltameter and Apparatus for varying the Load.

The voltameter was standardised several times by comparison with a potentiometer and gave very consistent results, the maximum difference between any two observations being less than 0·2 per cent. The figure obtained for the electrochemical equivalent of copper at this current density and at a temperature of 23° C. was 0·000329₂ grammes per coulomb.

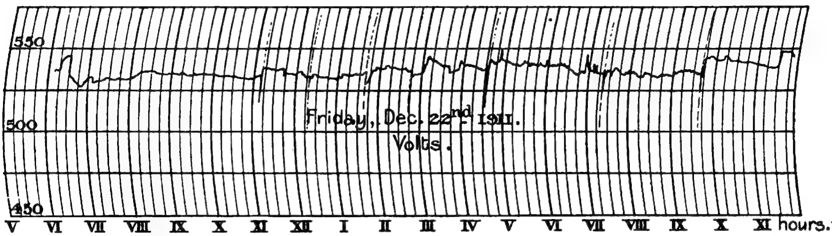


FIG. 3.

The plates were placed in the electrolyte immediately before the run commenced; and immediately after it was concluded they were removed from the solution, washed in distilled water, and dried in warm air. No difficulty was experienced in handling the plates, it being found that if they were well burnished before the run and the acid kept at full strength the deposit was quite adherent and hard.

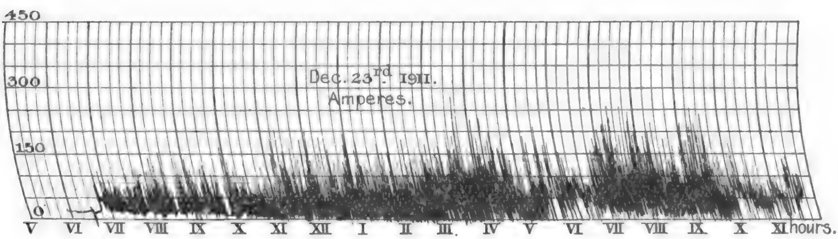


FIG. 4.

The time over which each variable load test extended was not less than 2 hours, the voltage on the meter-pressure circuits being maintained at 480 volts during this time.

The main current passing through the meters was varied by means of a moving contact consisting of a copper disc, the edge of which dipped into a mercury trough. On the axle of the copper disc was mounted a smaller brass disc around the circumference of which were drilled a number of holes to receive copper pins, which when the disc revolved passed through another mercury trough. The discs were

driven by a small motor through a worm and wheel-gearing (ratio about 600 to 1), the requisite time of contact being adjusted by varying

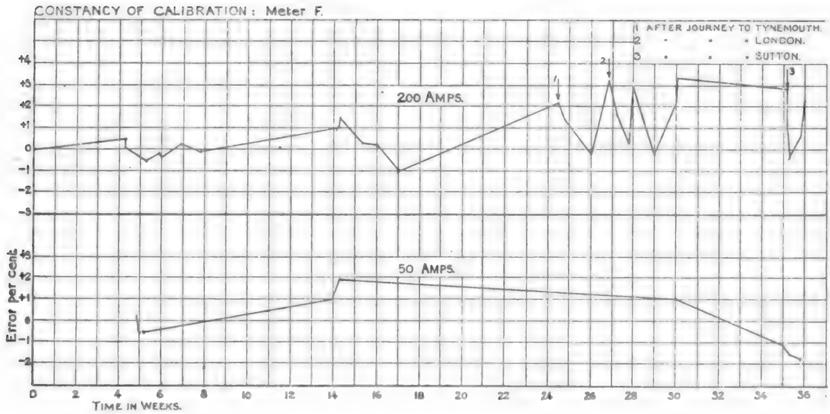


FIG. 5.

the motor speed and change pulleys, and by the arrangement of the number of pins on the disc. This contact was made to make and

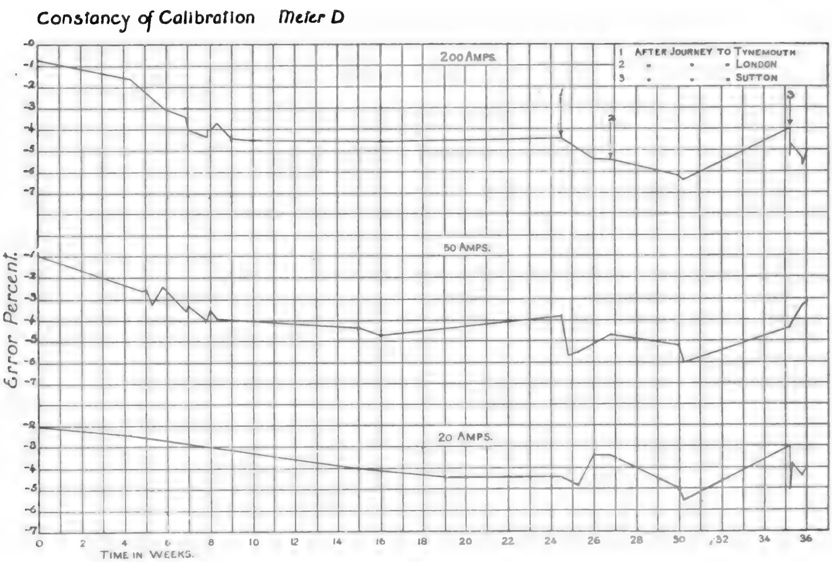


FIG. 6.

break the current through a solenoid relay which in turn actuated the mercury switch controlling the main-meter current.

Further particulars of this arrangement are shown in Figs. 1 and 2.

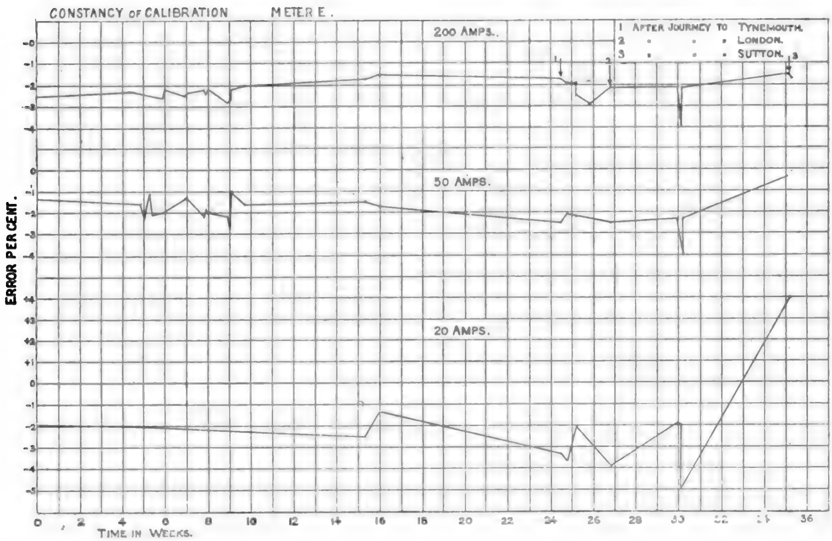


FIG. 7.

Before the tests with varying loads were commenced the meters were thoroughly tested at intervals over a period of three weeks

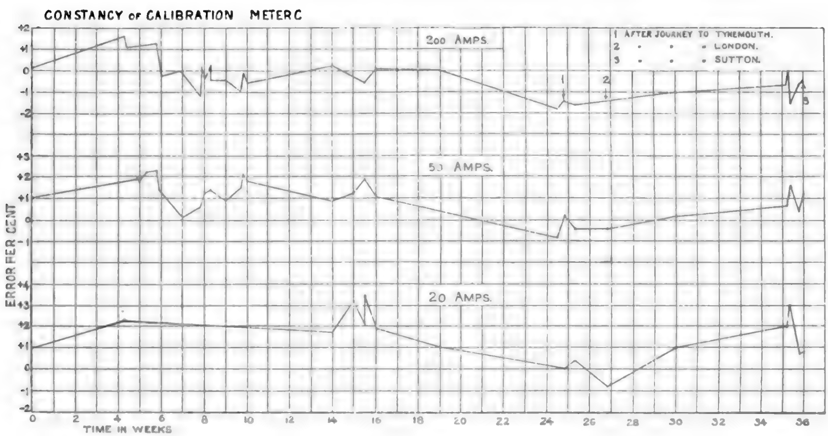


FIG. 8.

by short-run tests made by counting the revolutions of the rotor over a time of approximately 100 seconds, and by dial readings taken over

runs of several hours at full load. Short-run tests were also made both immediately before and after each test on variable load. Table I. gives the results obtained with variable load in terms of the mean of the

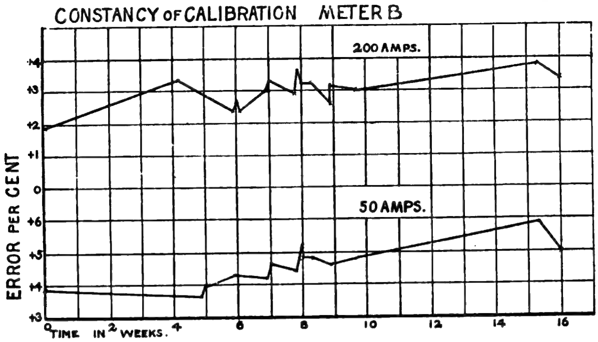


FIG. 9.

results of the short-run tests taken on the same day. The meter constant here used is the ratio of the true watt-hours to the watt-hours indicated by the meter. For the purposes of comparison in each case

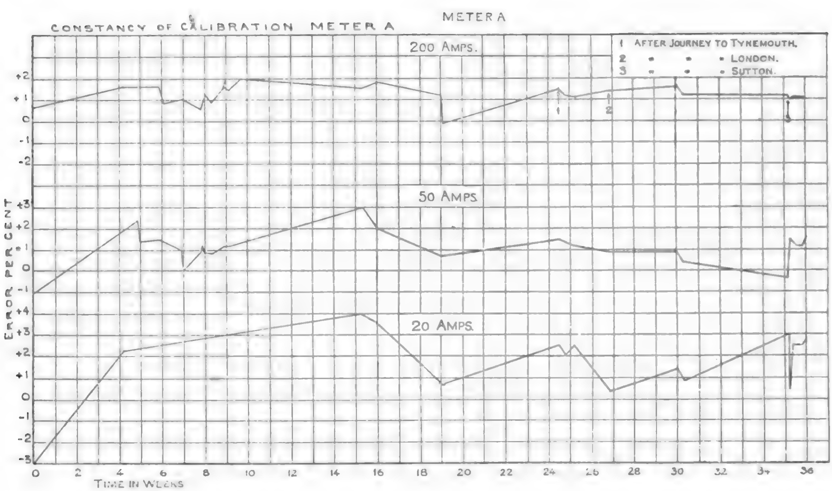


FIG. 10.

these have been reduced so as to bring the constant for steady load to exactly 100.

As will be seen from the curves in Figs. 5 to 15 the results obtained with the meters on steady load were not always consistent nearer than

Table I.

Variable Load.

Condition of Load.	Meter Constants.						
	A.E.G.	Aron.	B.T.H.	Chamberlain and Hookham.	Everett-Edgcumbe.	Evershed and Vignoles.	Siemens Bros.
Steady	100·0	100·0	100·0	100·0	100·0	100·0	100·0
Variable 1	99·5	99·8	100·1	101·1	99·8	100·9	100·0
" 2	99·3	99·9	99·9	99·7	99·5	100·9	99·7
" 3	99·5	99·3	100·5	100·8	99·7	101·4	100·2
" 4	99·2	100·0	100·2	100·0	99·6	100·9	99·4
" 5	99·5	100·1	99·8	100·4	100·0	100·4	100·3
" 6	99·7	98·2	100·3	99·9	99·4	100·2	99·2
" 7	98·9	100·0	100·3	99·7	100·0	99·8	100·0
Mean constant with variable loads	99·4	99·6	100·0	100·2	99·7	100·6	99·8
Meter period (*i.e.*, time taken to come to rest after switching off full load)	—	—	2 secs.	3·5 secs.	2·0	13·0	4·0

Condition of Load.

Load 1, 2 seconds at full load, 2 seconds at no load.
" 2, 2 " " 30 " ¼ "
" 3, 5 " " 5 " no "
Load 4, 5 seconds at full load, 5 seconds at ¼ load.
" 5, 5 " " 15 " ¼ "
" 6, 30 " " 100 " ¼ "
Load 7, 30 seconds at full load, 30 seconds at ¼ load.

within ± 1 per cent. The mean of the constants obtained with the variable load agrees with those obtained on steady load to within these limits, and shows conclusively that for all practical purposes there is no

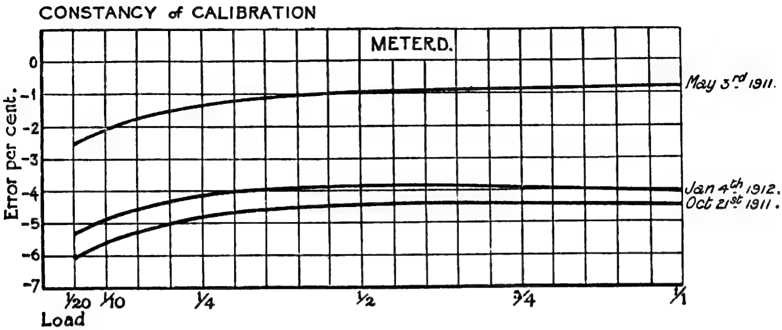


FIG. 11.

difference between the behaviour of any of the meters with a steady or a rapidly varying load; this confirms the conclusions of Messrs. Orlich and Günther-Schulze.

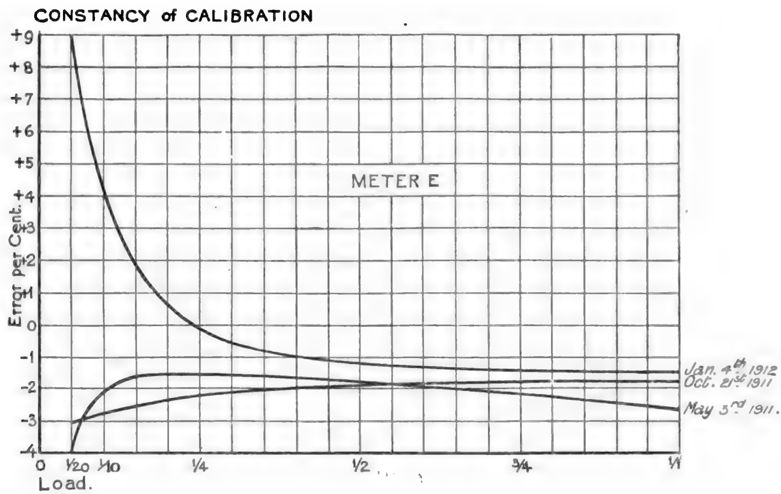


FIG. 12.

As a final check observations were taken over the first three weeks during which the meters were erected at Sutton. The load, as will be seen from the reproduction of a day's chart of current and voltage (Figs. 3 and 4), varies between 0 and 100 amperes, with occasional

kicks to 300 amperes. The average current, determined by a mean of the meter readings, was about 50 amperes. The B.O.T. units recorded by the meters, after being corrected in each case by the constant previously obtained at the laboratory, are given in column 1 of the following table, and the divergence of each meter from the mean of the whole six in column 2. It will be seen that the record of each meter agreed with the mean value to within ± 1 per cent., and in view of the fact that the average load was only equal to about one-quarter of the normal full load for the meters, and the possible error in testing was ± 0·5 per cent., this must be considered as very good agreement.

Meter.	(1)	(2)
		Per Cent.
Aron	7,605	+ 0·6
B.T.H....	7,590	+ 0·4
C. and H.	7,520	— 0·5
Everett-Edgcumbe	7,500	— 0·8
Evershed and Vignoles ...	7,560	0
Siemens	7,570	+ 0·1
Mean	7,560	

In the case of the results of the further tests which were made the meters are designated respectively A, B, C, D, E, and F, the order of designation bearing no relation to the order in which the previous results are given. The reason for this is that for the purpose of this portion of the investigation tests on a single meter of a type, while they show the order of change and reproducibility that may be obtained, are not necessarily representative of the whole type, and it is in order to prevent any misleading conclusions that this course has been adopted.

Constancy of Calibration.—The diagrams shown in Figs. 5 to 10 indicate the results obtained with the meters by steady load tests at various loads over the period of eight months covered by the tests. The observations have been plotted on a time basis, and the points joined up in order to indicate the changes more clearly. The lines joining the observation points do not necessarily represent the behaviour of the meter during the intervals between calibration. Figs. 11 to 15 show calibration curves for each meter taken at various intervals during the period covered by the tests.

During this period the meters were twice dispatched on journeys—once by goods train to Tynemouth and back, and once by carrier to London. The curves also include the results of tests made at the laboratory after the meters had been erected and run in the traction circuit at Sutton for one month. One meter was, unfortunately, injured

in travelling to Tynemouth, and this necessitated it being recalibrated, but otherwise there was no appreciable change in the calibration of any of the meters as a result of the travelling.

In the majority of cases the meters were consistent during the whole time to within about ± 1 per cent., the variation being in general rather more at the lower loads. In one case, however, the rate

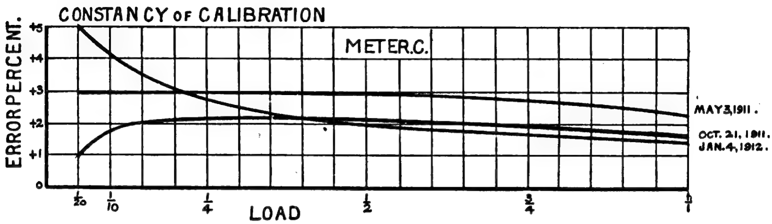


Fig. 13.

decreased by about 3 per cent. at all loads during the first six weeks, but after this time remained constant to within ± 1 per cent. With another meter the results obtained towards the end of the time varied by about ± 2 per cent. from day to day; this instrument was thoroughly examined by a representative of the makers, who, however, failed to find any reason for the variation.

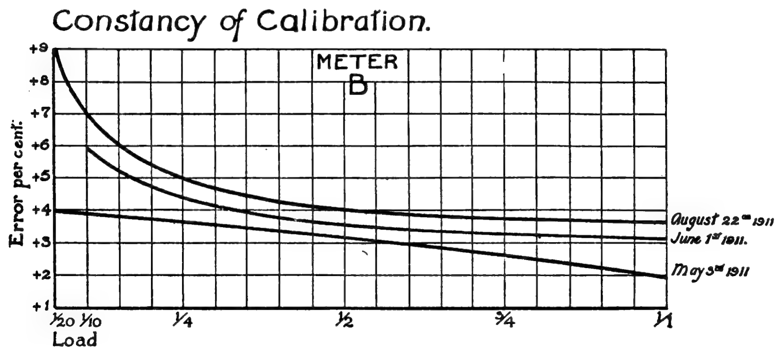


Fig. 14.

The meters were practically unchanged at the higher loads as a result of the month's work at Sutton; at the lighter loads, however, some fairly large changes did in some cases take place. In this connection it should be remarked that the changes coincided with a period during which the circuit breaker at the station came out several times owing to short circuits or other causes of excessive current, and

this seems to confirm the conclusions of A. Durand,* and also the results obtained with other meters at the National Physical Laboratory, that when a momentarily excessive current is passed through the meter the iron shield used to protect the brake magnets becomes slightly magnetised and affects the accuracy at light loads.†

Effect of Variation of Voltage.—The curves in Fig. 16 show the errors of the meters at normal voltage and at a voltage 10 per cent. above and below the normal. The changes are perhaps not excessive, but are large enough in some cases to require a correction if an accurate record is required at a voltage different than that at which the meters are calibrated.

Effect of Stray Fields.—So far as the authors are aware, no very definite data have been published as to the extent of the stray fields to which meters may be subject in generating stations. Experiments

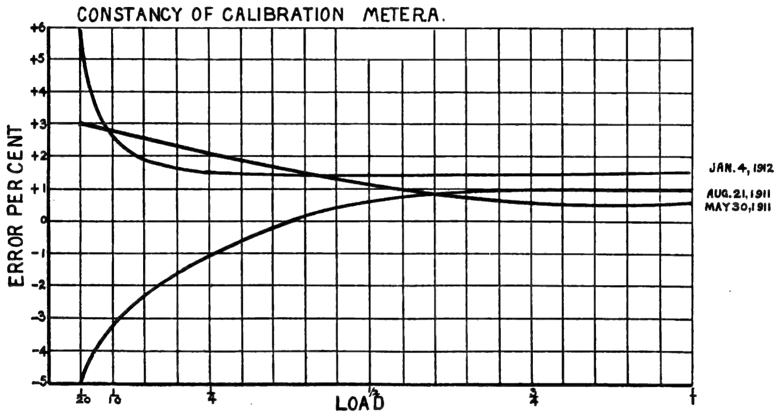


Fig. 15.

were therefore made by means of a coil carrying a current which was adjusted so that the field was equal to that which would be produced by a straight conductor carrying 1,000 amperes placed at a distance of 2 ft. from the meter. The curves, Figs. 17 to 20, show the result obtained when this field was placed in the position at which it produced the maximum change—*i.e.*, in the position most unfavourable to the meters. In the case of one meter there was no change in the rate owing to this field, and in another the difference was very small. In the cases of the other four meters, however, the changes at light loads are large, and it is obvious that this question is one of the greatest importance. Messrs. Ratcliff and Moore ‡ referred

* *Le Compteur Électrique, Atti del Congresso Internazionale delle Applicazioni Elettriche, Torino*, 1911, vol. 2, p. 743.

† A later examination seems to indicate that it is the steel spindle that has become magnetised and is affecting the accuracy of the meter at light loads.

‡ *Journal of the Institution of Electrical Engineers*, vol. 47, p. 3, 1911.

to the matter in their recent paper, while Durand mentions the case of a meter "which, placed between two cables carrying 1,500 amperes

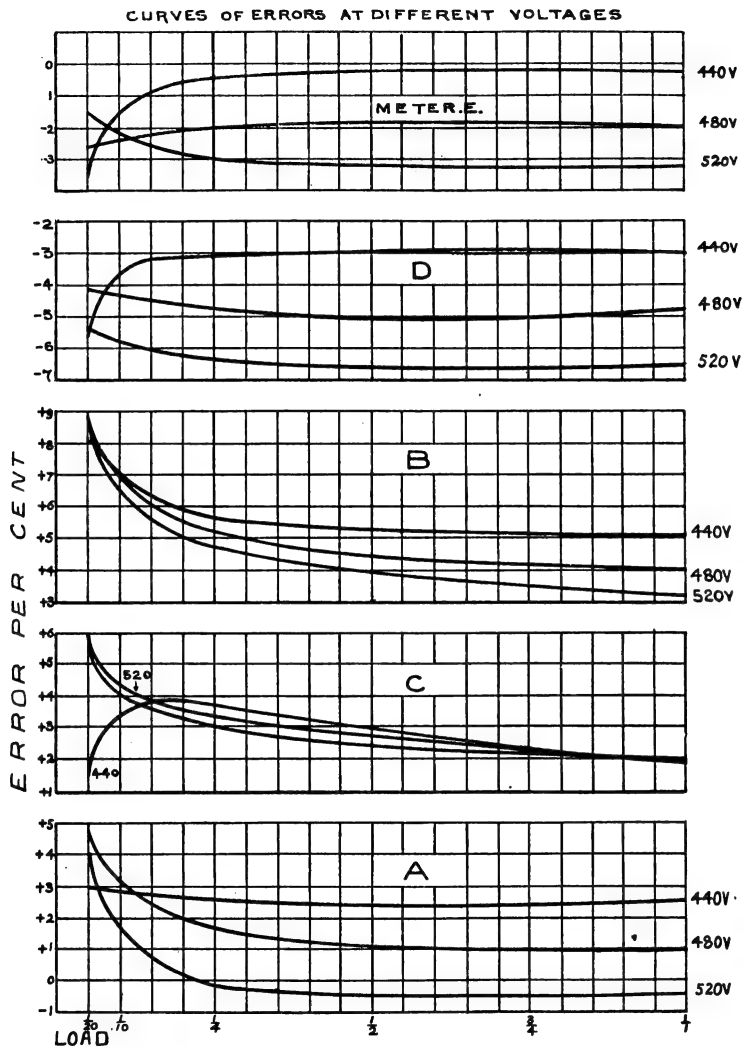


FIG. 16.

furnished by different machines, turned at no load in one direction or the other according to which cable was carrying current." Difficulties of this sort can be met by erecting the meters in such a position that

they will not be exposed to large stray fields. This subject is dealt with later.

Effect of Erecting the Meters out of Level.—The curves, Fig. 21, show the results obtained with the various meters when they were mounted 3° out of level; it will be seen that the errors at light loads are in most

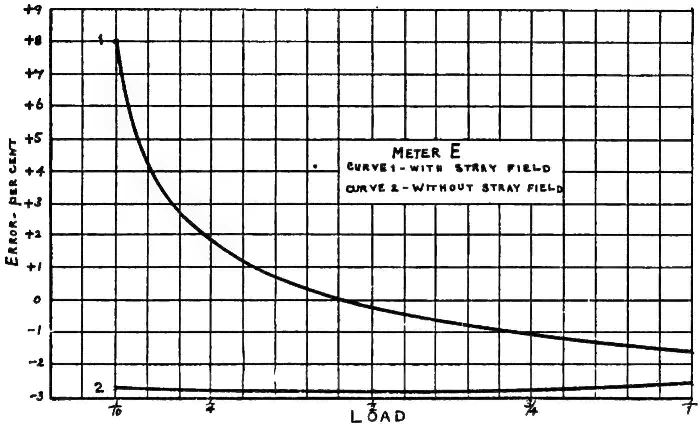


FIG. 17.

cases increased largely, while in one case the error at full load was altered by about 2 per cent.

Temperature Coefficient.—The temperature coefficient of all the meters tested was in no case greater than ± 0·1 per cent. for a change

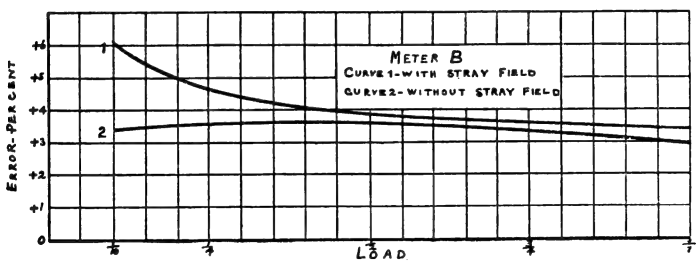


FIG. 18.

in temperature of 1° C., an amount which is probably negligible for most practical purposes.

In considering the question of obtaining an accurate measurement of energy by means of integrating meters it is probable that there are several factors, quite apart from any defects or inaccuracy in the instruments themselves, which have to be taken into account, and a few notes on some of these points may be of use.

Suitability of Meter for a given Load.—Often a meter is put into a circuit the current in which rarely, if ever, reaches the maximum for the average load, being often equal only to one-tenth of the full load for the instrument. This practice of allowing room for expansion, while possibly quite sound in the case of cables, switches, etc., is not very satisfactory for supply meters, which are more subject to variations at the lighter loads. In cases where the expansion is likely to be a matter of some years it would be far better to install at first a meter of small capacity, adding when the load increased another of the same size connected in parallel with the first, or by

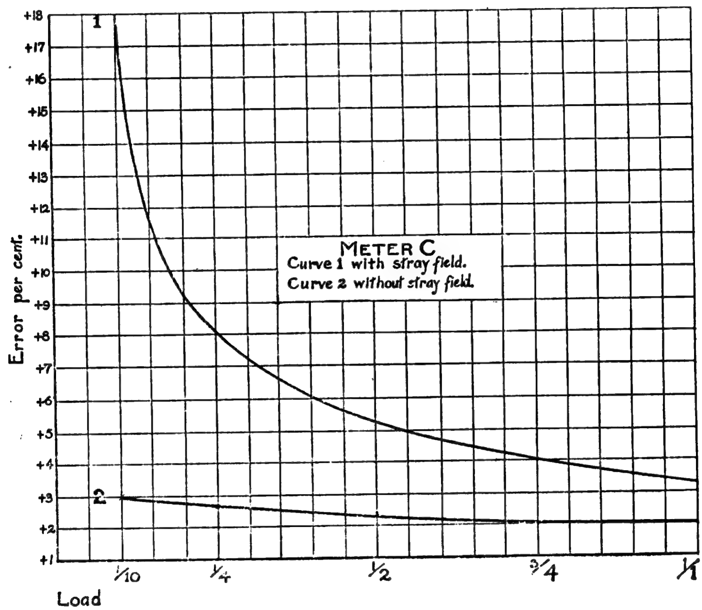


FIG. 19.

replacing it with a larger meter. This difficulty might be met by standardising the necessary parts of the meters. With the shunted type the substitution of a larger shunt and new gearing would then enable the meter to be used for a larger current. With the unshunted type the main current coils might be standardised sufficiently nearly so that any change in accuracy due to the substitution of larger coils could be corrected by means of the brake magnets.

Erection.—Temperature: Care should be taken to erect meters, especially those having a temperature coefficient, well away from any extraneous sources of heat, such as field-regulating resistances or switchgear. In most types of meter any compensation is dependent on all parts of the instrument being subjected to the same variations of

air temperature. More especially is this the case where the added resistance in the shunt circuit is wound of copper wire and mounted in a separate box. It is therefore important that the separate box should be placed in such a position that it will be subject to the same temperature variation as the meter, and will not be heated from an extraneous source of heat, or cooled by being placed in an air draught.

Stray Fields.—The effects on the accuracy of the meters of a stray field have been already remarked upon. It is obvious, however, that much larger fields than those used for this test are met with in practice. Messrs. Ratcliff and Moore mention that "one of the authors has seen a dynamometer watt-hour meter stop at about one-third full load, and actually reversed at one-quarter load, due to the effect of a stray

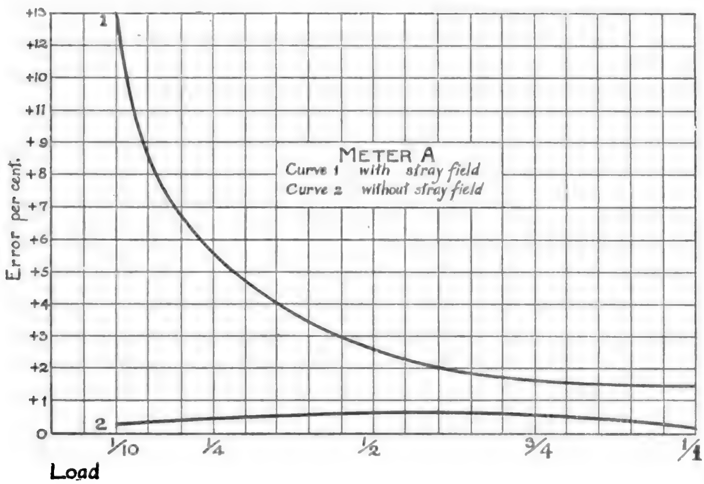


FIG. 20.

field." On this account, therefore, the possibility of stray fields should be carefully considered in selecting the position for erection, and it should be pointed out that there may be very large fields in the vicinity of the angle iron frame on which switchboards are usually mounted and near large circuit breakers of the magnetic type.

When the meters are erected a simple test can be made to ascertain if any stray fields are affecting them by disconnecting the main current leads from the meter and short-circuiting them, the voltage circuit being left connected across the mains. Under these conditions the effect of any stray field should be shown by a movement of the meter dials.

Connections.—It is preferable that the main current leads to meters should be run with the lead and return close to each other. Great care should be taken to see that good contact is made at the meter

terminals, as otherwise errors may be introduced into the readings owing to the rise of temperature in the instrument; this is a matter of great importance in the case of shunted meters, where bad contacts may lead to very large errors. In the cases of two meters recently tested in the condition in which they were received it was found that in one (a 4,000-ampere meter) the watts lost in the contacts were almost equal to those dissipated in the instrument itself, and that the rate of the meter, after it had been run for 1½ hours, had increased by about 5 per cent.; and in another (a shunted meter), when first tested, the reading was found to be 30 per cent. too low, while after the contacts were cleaned it was correct to within 2 per cent.

Levelling.—It will be seen from the results given in Fig. 21 that a slight difference in level affects seriously only the accuracy of the lower loads; as, however, it is important that these should be accurate it is desirable that the meters should be carefully levelled. Aron clock meters can be levelled by the small plumb-bob affixed inside the case, and motor meters by the well-known method of placing a coin or small weight on the outer periphery of the brake disc and adjusting the level so that the weighted disc does not move when the meter case is tapped. In the case of the oscillating type meter, where the disc is not able to make a complete revolution, the method adopted by the authors was to time two oscillations with a small steady current, the level of the meter being adjusted until the time of oscillation was the same in each direction.

Testing.—With most of the types of direct-current watt-hour meters it is possible to obtain under proper conditions an accuracy of test to within ± 0.5 per cent. This, however, probably applies only where the measurement of current and pressure are made directly by a potentiometer. The possible errors are made up as follows: Potentiometer and accessories $= 0.1$ per cent., chronograph $= 0.2$ per cent., error in observing revolutions of disc $= 0.2$ per cent. (It is probable, of course, that a greater degree of accuracy can be obtained by taking the mean of a number of observations.) Where direct deflection instruments are used for the measurement of power the possible error is of necessity somewhat larger. Assuming that the errors of both ammeter and voltmeter have been previously determined by potentiometer to 0·1 per cent., the possible error in reading the instruments at one-half of full-scale reading cannot be less than one-tenth of a scale division, and this represents an error of 0·2 per cent. on both volts and amperes. The errors in the different instruments may, of course, cancel each other out; but it is never safe to rely on this happening, and the accuracy of tests under these conditions cannot therefore be considered as being nearer than ± 1 per cent. Speaking generally, direct-current watt-hour meters are consistent to within ± 1 per cent. at the upper loads, and it is clearly shown by the results before mentioned, obtained at Sutton, that the records obtained under working conditions when corrected by the constants obtained by the tests should be correct nearly to within this limit. Until the tests before mentioned regarding the permanence

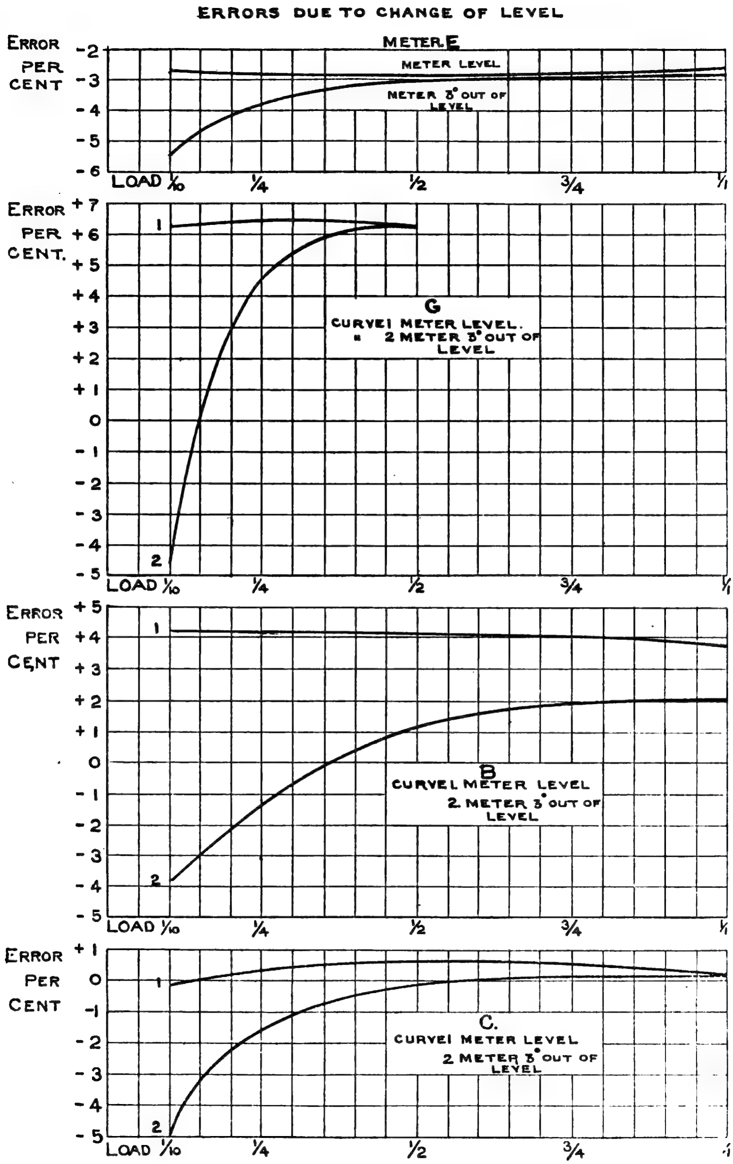

ERRORS DUE TO CHANGE OF LEVEL
METER E
METER LEVEL
METER 3° OUT OF LEVEL
ERROR PER CENT
LOAD 1/10
1/4
1/2
3/4
1/1
G
CURVE 1 METER LEVEL.
" 2 METER 3° OUT OF LEVEL
B
CURVE 1. METER LEVEL
2. METER 3° OUT OF LEVEL
C.
CURVE 1 METER LEVEL
2 METER 3° OUT OF LEVEL

FIG. 21.

of the calibration are completed, we are unable to state any very definite time over which the meters may be expected to remain constant, but in the case of a meter used to measure a large output it is recommended that it be tested and, if necessary, cleaned and adjusted once every six months.

In making tests in the laboratory or test-room there are one or two points which are sometimes overlooked and which it is desirable to emphasise.

Pressure Circuit.—The pressure circuit should be connected to the mains for several hours before commencing the test. This applies more particularly to those meters in which the series resistance is of copper and is situate inside the meter. It is often assumed that 1 hour is sufficient for the resistance to attain to its final temperature; but it must be remembered that the heating from the resistance coils produces a rise of temperature inside the meter case, and thus by increasing the resistance of the brake disc causes the meter to run fast. One hour is not sufficient for the various parts of a meter to attain to a constant temperature under these circumstances.

In addition to the usual test at various loads, made preferably with a chronograph as distinct from a stop-watch (chronograph is the name generally given to a centre seconds watch, the hands of which are put in and out of gear with the movement, while by "stop-watch" is meant a watch in which the whole movement is stopped or started), it is necessary that the meter should be run for a considerable time at full load in order to ascertain the extent of the error due to heating. The time necessary will, of course, depend on the type of meter—some will attain to their maximum in 1 hour while others may require as long as 5 hours; in all types, however, the main portion of the heating will take place in the first hour, and a short-run test taken at the end of that time will indicate very well whether the test need be continued further. In more than one meter tested by the authors the accuracy changed by about 5 per cent. as a result of running for 5 hours at full load.

In testing direct-current watt-hour meters at the National Physical Laboratory the meter is first levelled, all connections made, and the voltage circuit connected to the mains several hours (usually overnight) before the test is commenced, a small current, say about one-tenth of the maximum load, being passed through the meter for about 1 hour. The current and pressure measurements are made directly by a potentiometer. The meter is tested at a number of loads by counting the revolutions of the rotor, the time for each test being not less than 100 seconds; it is then run for 1 hour at full or at any definitely specified load, the current and voltage being kept constant during this time so that the observations of the dial readings afford a check on the errors computed from the constant stated by the makers. After this run the meter is re-tested at various loads by short-run tests in order to ascertain the extent of any difference which may have occurred due to elimination of friction, heating, etc. If the results obtained show any large

change due to running or are in any way exceptional, further checks are made, probably after some days have elapsed, a measurement being made of the temperature coefficient and of any other points which are suspected as being responsible for the discrepancy.

Tests in Position.—Tests made in position are often of very little value. In the author's opinion there is no direct-current meter at present on the market which can be relied upon to integrate a load sufficiently accurately to be used as a standard by means of which other meters can be checked, and in some supply stations it is difficult to obtain a steady load and satisfactory arrangements for installing and connecting in the circuit suitable testing instruments. Moreover, in the case of a meter which may be affected by external stray fields it is by no means clear that a test *in situ* will give an accurate idea of the behaviour of the meter under all conditions of load. The stray fields are not necessarily produced by the particular circuit in which the meter is connected; but may be caused by a totally different circuit, and under these conditions a test cannot be satisfactory unless it is certain that this stray field is constant; from all points of view, therefore, it seems to be most satisfactory to erect the meter in such a position that it is unaffected by stray fields or anything else which may impair the accuracy, and to have it tested from time to time under conditions, both as regards apparatus and time, in which the errors can be accurately determined and any special points fully investigated.

The thanks of the authors are due to Dr. Glazebrook for his interest in the work, to the various firms who have lent meters for the tests, to the South Metropolitan Tramways Company for permission to install the meters at their Sutton station, to Mr. C. Turnbull, and to Mr. W. H. Withey for generous assistance in the preparation of the drawings and diagrams.

APPENDIX.

Permanent Change due to Momentary Excessive Loads.

During the interval between sending in and reading the paper the effect on the accuracy of the motor meters of a momentary excessive load, to which they may be subjected when a fuse blows or a circuit breaker comes out, has been further investigated. Duplicate meters were obtained for the purpose, and these were tested for accuracy both before and after a current of about 6,000 amperes, *i.e.*, 30 times the normal full-load current, had been passed through them. The results of these tests are shown by the curves, Figs. 22, 23, 24, and 25. The second curve was in each case taken after a sufficient lapse of time, so that any purely temporary effect, such as heating, would not affect the results. It will be seen that the meters A, B, and D had definitely increased in speed by from 4 to 5 per cent. at all loads, this seeming to show that the brake magnets are insufficiently shielded. In the case of meter E, while there is a large difference at the lighter loads (about

8 per cent. at one-tenth load) the error at full load is much less. The change here is obviously due to some part of the meter having become

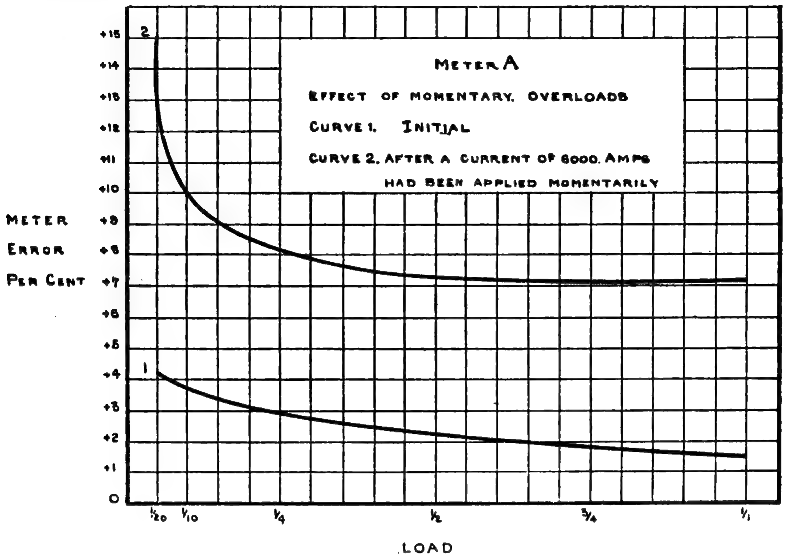


FIG. 22

magnetised. In the footnote, page 13 of the paper, this is ascribed to the spindle, which was undoubtedly strongly magnetised; further tests,

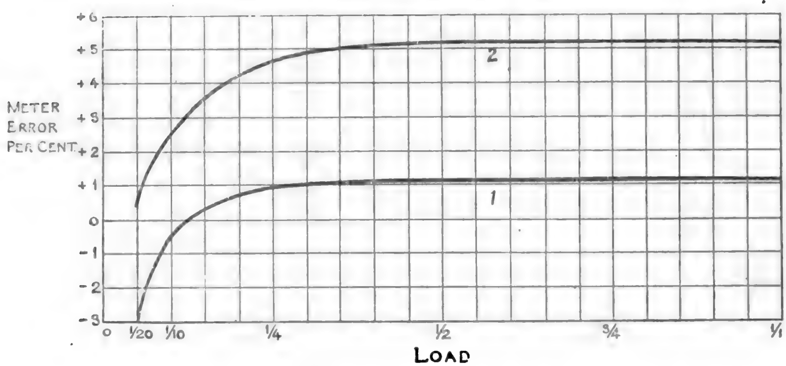


FIG. 23.—Effect of Momentary Overload.

METER B.

Curve 1. Initial.
Curve 2. After a current of 6,000 amperes had been applied momentarily.

however, proved that this was not affecting the accuracy. Two meters, similar in all respects with the exception that in one the spindle was of phosphor-bronze and in the other of steel, were supplied by the makers

of this type of meter, and when tested gave practically identical curves after the application of the overload current. The question of the iron

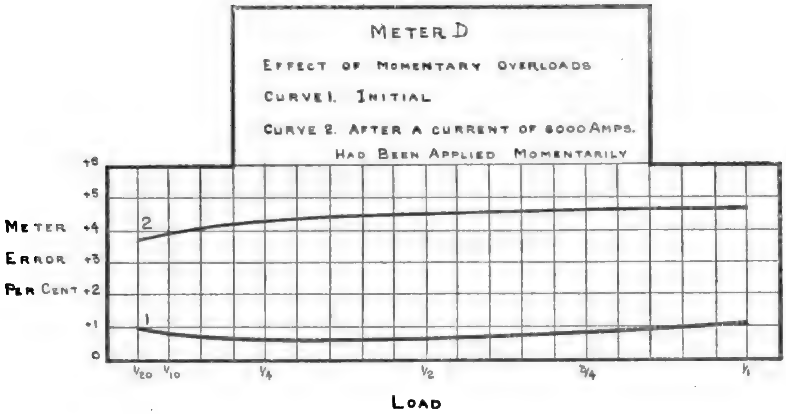


FIG. 24.

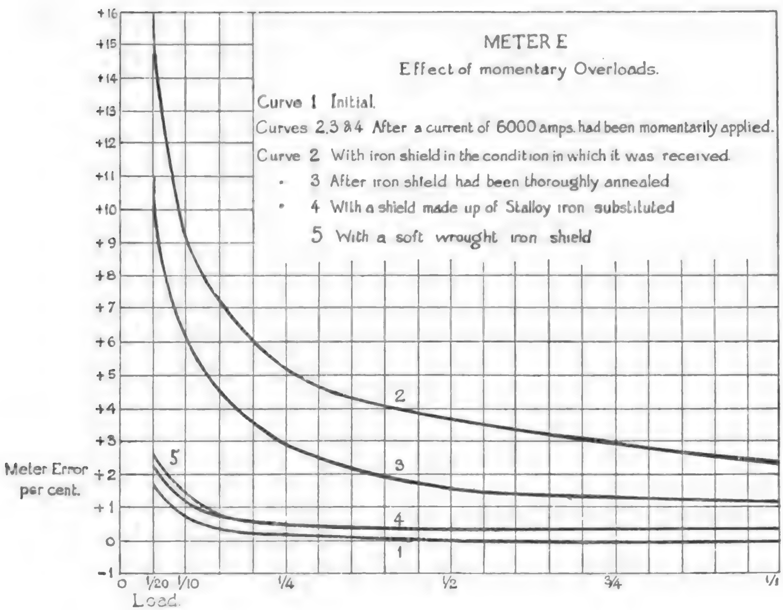


FIG. 25.

shield round the brake magnets was then investigated, a number of tests being made, the results of which are shown in Fig. 25. Curve 1 shows the initial meter errors, and curve 2 the errors after the overload

current had been applied. In the case of curves 3, 4, and 5, Fig. 25, it was necessary to dismantle the meter in between each of these tests, and it was therefore calibrated each time to be nearly the same as curve 1, or, in the case of slight divergence, the results were corrected in order to make the curves comparative. After trying the effect of surrounding the cast-iron shield with sheets of stalloy iron, it was finally removed and replaced by a box built up out of sheets of stalloy iron, with the result that the curve taken after the overload agreed with the first to within 0·5 per cent. A somewhat similar result was obtained with a shield supplied by the makers and said to be of wrought iron. Curve 3 (Fig. 25) gives also the results when the original cast-iron shield was thoroughly annealed—the change in this case is less than before annealing, but it is still considerable.

The question of change in rate due to excessive currents is one of great importance, and in view of the fact shown by these experiments that the difficulty can be overcome by the use of proper materials, it is to be hoped that the meter manufacturer will give attention to it.

Constancy of Calibration.

The observations as to the constancy of the calibration of the meters have been carried on for a further period of seven months, this making a total period covered by the tests of fifteen months. During the last eight months of this time the meters have been working in a traction circuit. The later observations indicated that some of the meters were changing, the differences in the readings after they had been corrected by the previously determined constants amounting to as much as ± 3 per cent. from the mean of the five meters. They were therefore brought back to the Laboratory for examination, and it was found that while the change in the case of meters A, B, and C was not greater than ± 1 per cent., meter D had decreased in rate by a further 2 per cent., this making a total change of 6 per cent.; E had increased by 2·5 per cent., and F had increased by 3 per cent. Under these circumstances, therefore, the tests are not being further proceeded with.

Any conclusions as to the time which meters may be expected to remain constant under running conditions are necessarily inconclusive when only a single meter of each type is kept under observation. In this case, however, the meters had been proved by the previous tests to be in sound condition, and it may therefore be fairly said that in cases where a record is required to an accuracy of 1 or 2 per cent., it is advisable to have the meters checked once a year.

ELECTRICAL METERS ON VARIABLE LOADS.

By DAVID ROBERTSON, D.Sc., Associate Member.

(*Paper received September* 1, 1911, *and read before* THE INSTITUTION 9*th May*, 1912.)

CONTENTS.

SUMMARY.

The paper deals both theoretically and experimentally with the behaviour of electricity meters on variable loads. It is shown that an eddy brake meter without fluid friction and with perfectly compensated solid friction is correct on all loads whether steady or not; the extra record made during deceleration always exactly compensates for that lost during acceleration.

Solid friction makes the loss of record while the speed is rising exceed the gain while it is falling; while fluid friction, even if compensated

for steady loads, has the reverse effect. The proportional starting and stopping error due to solid friction increases indefinitely as the duration of the load is made less and less, while that caused by the fluid friction only approaches a finite limit of the same order as the amount of the friction itself.

On a rectangular-wave cyclic load the error due to solid friction is constant at all frequencies above that at which the rotor just comes to rest each cycle, and is such as to make the meter run at the same speed as it would with a steady load equal to the mean. The fluid friction error increases with the frequency, but is less than the starting and stopping error.

Experiments made at the Merchant Venturers' Technical College and at the Devonport and District Tramways are described, and the results given and discussed. They confirm the theoretical conclusions but show that the effects are small on a tramway load.

Introduction.

The behaviour of a meter of the motor class when subject to variable loads, such as that of a tramway system, has several times been called into question by those who have to pay according to the record of such meters. It has been suggested that they are bound to record against the consumer on such loads because of the fact that they continue to run for a little while after the load is shut off, the allied fact on the other side, viz., that they do not immediately attain full speed when the load is applied, being often overlooked.

The author was recently called upon to decide a dispute of this kind, in which the engineer had apparent support for his contention from the discrepancies between the official meters and another of a different type which he had in circuit as a check, both being supposed to be accurate on steady loads. However, when tested *in situ* the discrepancies were accounted for by steady load differences between the meters, while both theoretical considerations and the results of a control experiment on new meters of each kind showed conclusively that on a tramway load neither of the meters behaved appreciably differently from what their steady load characteristics would lead one to expect.

In view, however, of the fact that a preliminary examination of the theory showed that some meters would behave differently on a rapidly variable load, and also of the general importance of the matter, it was decided to carry out further experiments devised so as to magnify such effects if there were any, and with the kind co-operation of the manufacturers who lent or gave samples of their instruments for the purpose, this has been done. It was originally intended to carry out a much more extensive series of experiments than has actually been made; owing to illness of the author they were suddenly cut short, but not before sufficient results had been obtained to show the nature of the phenomena involved and conclusively to verify the theory.

Theoretical Deductions for Motor Meters.

The mathematical theory for several special cases is given in an appendix at the end of this paper, and the following is a general summary of the conclusions to be drawn from them. As is well known, the law connecting the resisting torque with the speed must be the same as that connecting the driving torque with the current, or power, being metered if the meter is to be accurate on all loads. This agreement can only be approximately attained in practice, but if it could be made perfect, then, however complex the law might be, the meter, when properly calibrated, would be correct on all steady loads and also on all variable loads which change sufficiently slowly to make the inertia torque negligible. But it would not necessarily be accurate on loads which vary sufficiently rapidly to produce appreciable inertia torques on the rotor of the meter.

In ordinary meters we can conveniently divide the resisting torque into three components—solid friction torque, eddy-current torque, and fluid friction torque—and assume these to be respectively constant, proportional to the speed and to the square of the speed. None of these assumptions is quite true, but within certain ranges for each the deviation can safely be neglected. The solid friction increases very considerably at low velocities, especially when the speed is almost zero. The eddy-current torque increases less rapidly than the speed at high speeds and reaches a maximum at a certain speed, beyond which it diminishes, owing to the inductance of the eddy-current paths. The action is essentially the same as in the rotor of an induction motor, and the torque speed curve for the eddy-current brake is of the same type as the torque-slip curve for the induction motor, but at all ordinary meter speeds the reactance effects are quite negligible and the deviation from the proportional law is inappreciable. Fluid friction changes law at a certain critical speed which depends on the constants of the fluid; below that speed the fluid frictional torque is proportional to the speed instead of to its square.

Fluid Friction Meters.

A meter in which the main resisting torque is fluid friction, such as in the old Ferranti and Schallenberger meters, may be termed a fluid friction meter, and may be dismissed at once. If everything else but fluid friction were absent, and it retained the square law at indefinitely small speeds, such a meter would never stop when once started and would record an infinitely great amount after the load was switched off. Also, on a rapidly variable cyclic load whose frequency is high enough to make the speed practically constant throughout the cycle, the mean driving torque, on which the speed depends, is proportional to the mean square of the load, and so the record would give the R.M.S. instead of the mean load. With a rectangular-wave load of high frequency, on for one-fourth and off for three-fourths of each cycle, as in the experiments referred to below a fluid friction meter would

record twice as much as it ought. Actual fluid friction meters are not quite so bad because they always have some solid friction which prevents anything like continuous rotation when the load is off.

Eddy-current Brake Meters.

In practically all modern motor meters the main control is an eddy-current brake, and these may be termed eddy brake meters. When the solid friction is exactly compensated and fluid friction absent, the mean current or power being metered will be strictly proportional to the

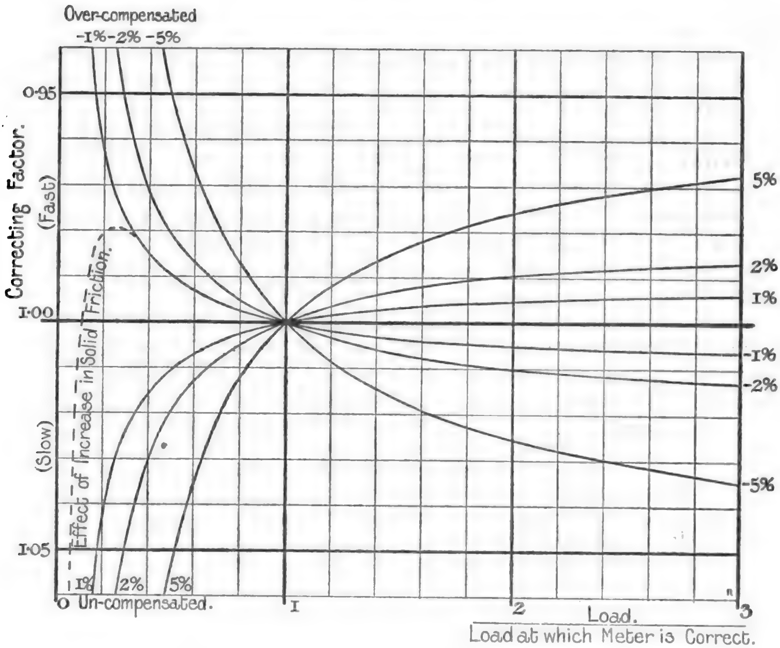


FIG. 1.—Steady Load Characteristics with Constant Solid Friction.

mean speed, and the meter, if properly calibrated, will always record correctly whether the load changes rapidly or slowly, whatever the waveform of the load may be, and however much inertia the rotor may have. Like the fluid friction meter, it would slow down asymptotically, but unlike it, it would only record a finite amount while stopping, and that would be exactly equal to the loss of record while it was getting up speed. Its steady load characteristic is a horizontal straight line.

Solid friction alters this steady load characteristic into a rising curve as shown in Fig. 1. On rapidly varying loads solid friction makes it record too little as compared with its rate at a steady load equal to the maximum, as shown in Fig. 2. The rate under variable load,

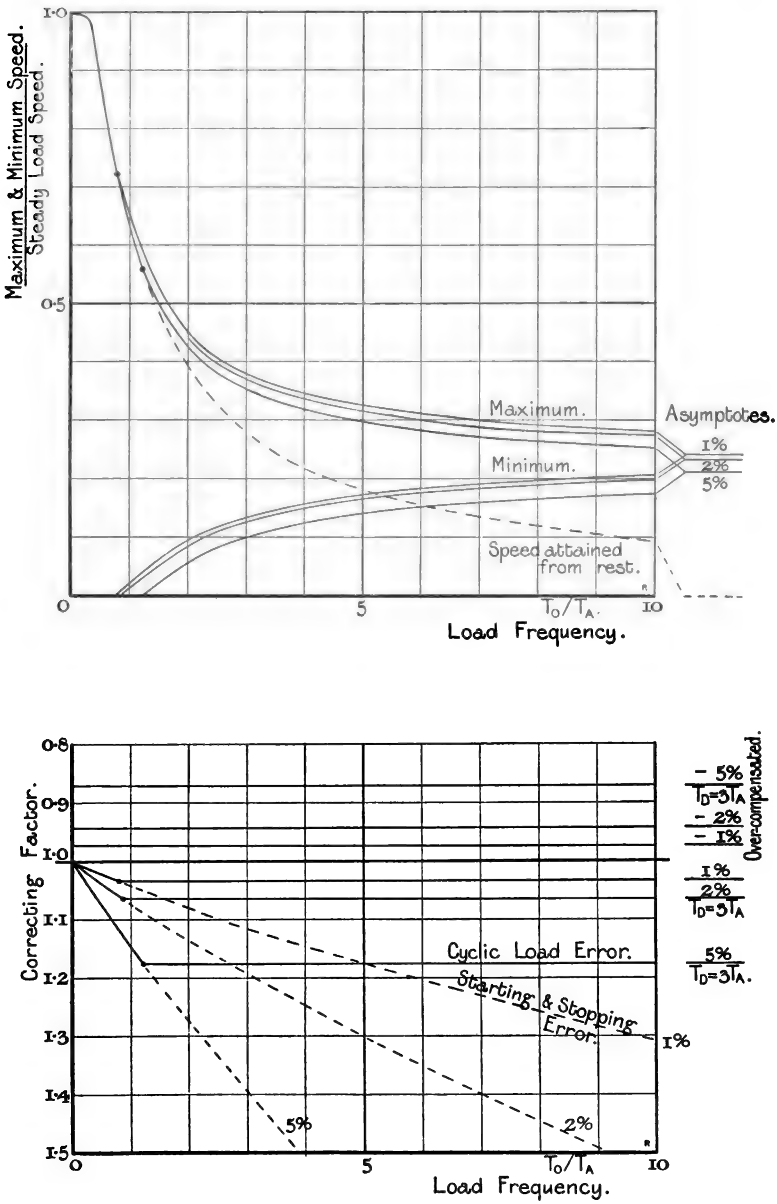


FIG. 2.—Effect of Constant Solid Friction with Rectangular Wave Load.

however, agrees with that at a steady load equal to the mean load. The starting and stopping error increases indefinitely as the duration of the load is diminished, but under the worst conditions likely to occur in practice the variable load error, compared with the rate at maximum load, is of the same order as the ratio of unbalanced frictional torque to the eddy brake torque at the speed corresponding to the maximum load; it gets *less* as the load on the meter is made greater.

In electrical energy meters (watt-hour meters) the solid friction is generally compensated by putting some field turns in the shunt circuit, so that there is always a driving torque whether there is a load or not.

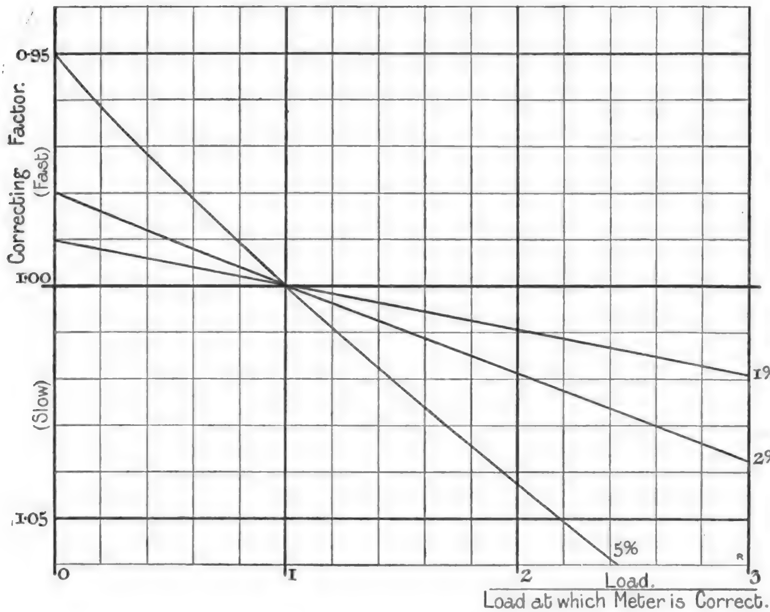


FIG. 3.—Steady Load Characteristics with Fluid Friction.

With the object of getting a low starting current, the position of these coils is generally adjusted so that the rotor will just not continue to rotate when the load is removed. Creeping is then liable to occur if the meter be removed to a place where it is subject to vibration, or where the voltage is above normal, and the solid friction is, as a rule, considerably over-compensated at the running speeds. Such over-compensation may be regarded as a negative friction, and produces the opposite effects from friction itself. Its effects are also shown in Figs. 1 and 2. Owing to the variation of the solid friction, perfect compensation can never be obtained in this way (there is a way in which it probably could be done, but this has not yet been tried), and

so they are generally under-compensated at low loads and over-compensated at large ones. The dotted lines in Fig. 1 show the sort of effect which the change of friction produces. It is the unbalanced solid friction which makes the rotor come to rest in a definite time, that time depending on the inertia of the rotor.

When there is fluid friction, but no solid friction, the steady load characteristic becomes almost a straight line sloping downwards as in Fig. 3. The lines would be exactly straight if the speed of the meter

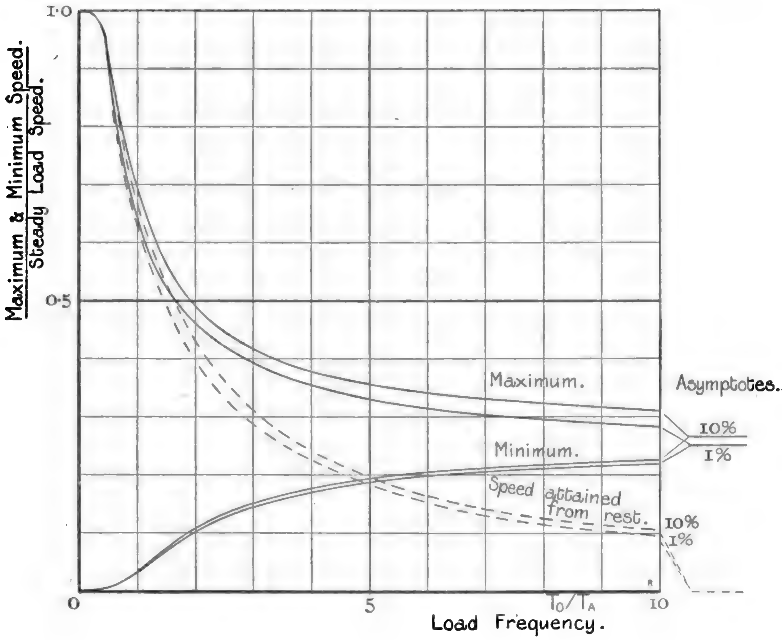


FIG. 4 (*Upper*).—Effect of Fluid Friction with Rectangular Wave Load. (Assumes Brake and Flux unchanged by Load.)

were taken as abscissa instead of the load. The fluid friction can be more or less compensated for steady loads by a series coil which alters the division of the flux between the motor and brake portions in such a way as to diminish the eddy-current torque relative to the driving torque at the larger loads. But even if this adjustment were perfect at steady loads the meter would run faster than it ought at variable loads (see Fig. 4). The limiting error, whether starting and stopping or on a cyclic load, is of the same order as the ratio of the fluid friction torque to the eddy-current torque at the speed corresponding to the maximum load, and it is *greater* for large loads than for small ones.

When both solid and fluid friction are present, the characteristics are intermediate between those considered. Each kind of friction tends to correct the errors due to the other. Sometimes the one and sometimes the other will predominate according to the load and other circumstances. Figs. 5 and 6 give the characteristics for such cases. The curve in Fig. 5 for 5 per cent. solid and 1 per cent. fluid friction, if carried considerably further to the right, would give an excellent steady load characteristic, such as that obtained from the

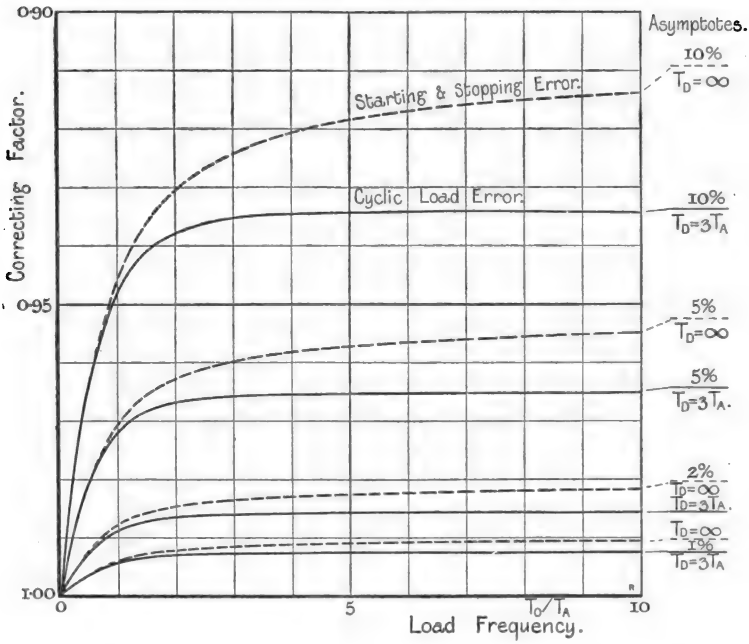


FIG. 4 (*Lower*).—Effect of Fluid Friction with Rectangular Wave Load. (Assumes Brake Flux unchanged by Load.)

modern Ferranti meter. Of course, it should be remembered that the proportion of each friction with a given meter varies with the load, that of the solid friction being inversely and of the fluid friction approximately directly proportional to the load, while the proportion of the latter to the former varies approximately with the square of the load.

EXPERIMENTS.

In the experiments a variable current was passed through the main coils of all the meters, while a constant voltage was maintained on the shunts of the energy meters. The electricity passed through was

measured by a copper voltameter, and the voltage by a Nalder volt potentiometer and Weston cell. A shunted moving coil instrument and a Kelvin balance were also included in the main circuit, and gave readings of the mean and R.M.S. values of the current when the frequency was high enough.

A sketch of the voltameter is given in Fig. 7, as it proved to be a very convenient form for rapid work, and lends itself to designs for large currents. The size of cathode chosen was limited by the balance used for weighing; by having a little loop of thread on the balance hook the plate could just be made to hang freely in place, its bottom edge resting

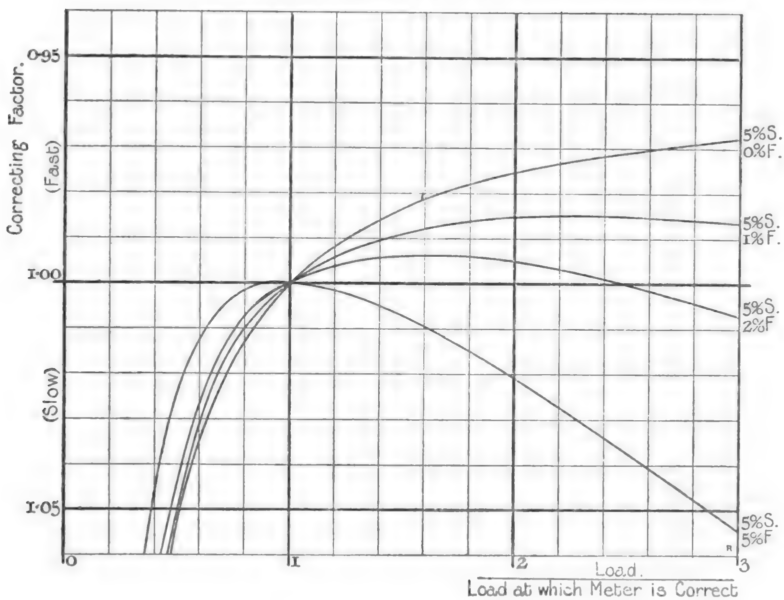


FIG. 5.—Steady Load Characteristics with both Solid and Fluid Friction.

on the wire supporting the scale pan. With two cathodes the voltameter can be used up to about 25 amperes. For larger currents it will be found more convenient to connect several units in parallel than to put a larger number of plates on one stem owing to the less accessibility of the inner plates.

The variations of the current were obtained by means of a motor-driven rotating switch, which completed the circuit during one-quarter of each revolution. The load thus had a form-factor of 2. A few preliminary runs were made with a resistance in parallel with the switch, but the effects were then found to be less than when the current was reduced to zero, and so all further experiments were made without

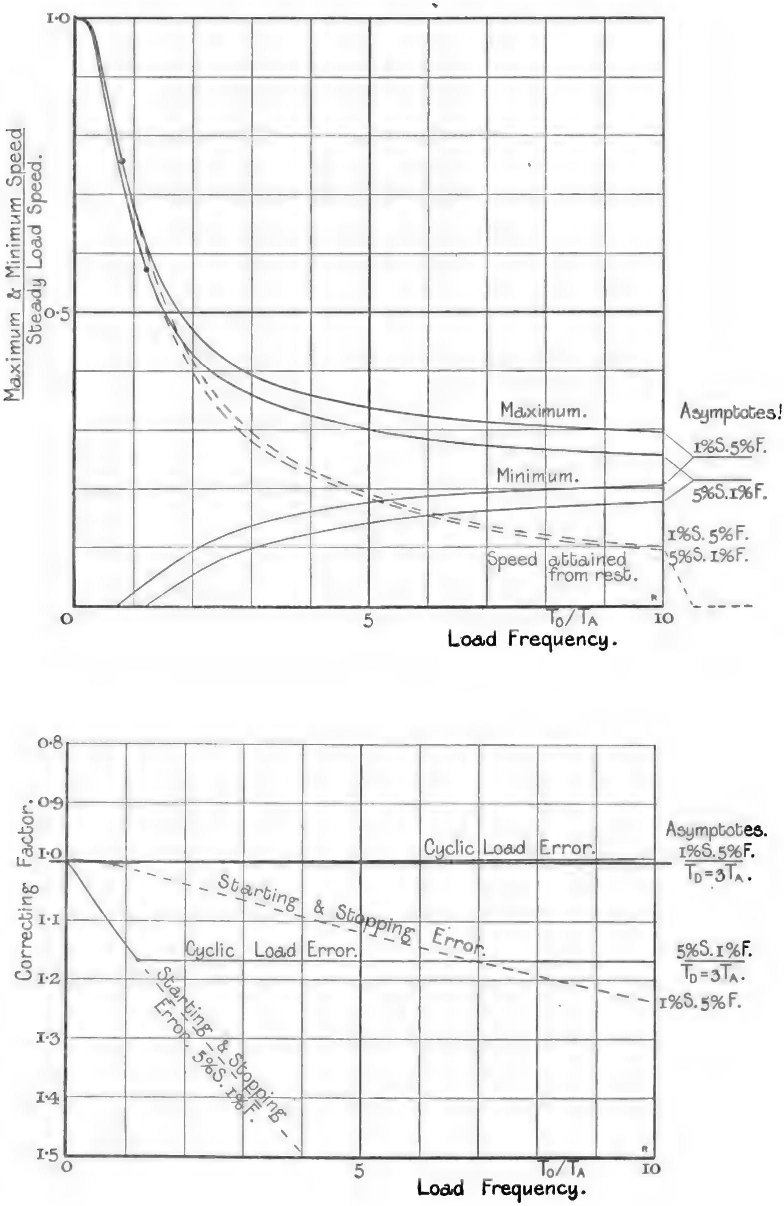


FIG. 6.—Effect of both Solid and Fluid Friction with Rectangular Wave Load.

that resistance. In the first series of experiments no attempt was made to keep the maximum current always the same, and it varied from about 20 amperes down to about 16 amperes, most of the meters being of the 10-ampere size. The results of these tests are plotted for most of the meters, and are distinguished by circles. One or two meters showed some evidence of a slight permanent change of constant under this treatment. They had not all arrived when this series was commenced, but were added to the circuit as they came in, causing a drop in the maximum current.

In the second series, which is the more reliable of the two, the load

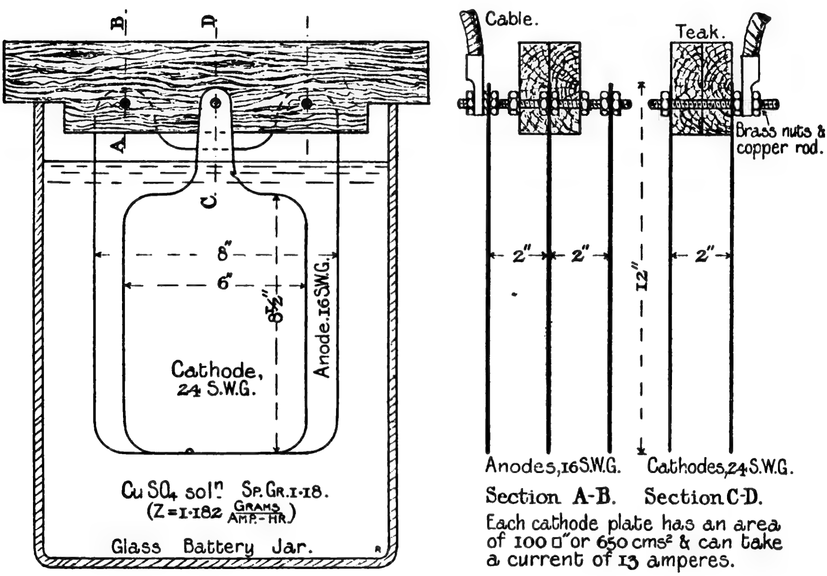


FIG. 7.—Copper Voltameter for 25 Amperes.

was adjusted at the beginning of each experiment to exactly 10 amperes, the rotating switch being short-circuited for a moment to allow this to be done. It was then left running for exactly two hours altogether.

Scales were added to the wheels of those meters whose dials did not give a sufficiently fine reading, and the records of these were afterwards reduced to dial readings from the known wheel ratios. Some of these scales were awkward to read, and liable to be misread, but after a little practice it is probable that few mistakes were actually made. Throughout all the tests the meters were run for some time before commencing the experiments, but they had, of course, to be stopped while the readings were being taken and checked. This took from an hour to half an hour.

The switch was a simple ring of brass with a projection on one side let into a hard-wood block, so as to give a smooth surface. The wood, however, wore into a hole where contact was broken, and so after a time there was a sort of quick break. Copper brushes which had already been made for another purpose pressed on the ring and projection. At all except the highest speeds the switch was found to be quite satisfactory; but at high speeds the sparking was rather violent, and the contact resistance considerable. The switch was fixed directly on the shaft of a 5-H.P. 500-volt 1,200 revs. per minute motor, and the means of varying the speed are of interest. The field coils were put across the normal 500 volts, and the armature on whatever voltage was necessary for the speed required. As a steady low speed could not be obtained with free running on very low voltages the machine was coupled to its neighbour, a polyphase alternator, which was short-circuited on itself phase by phase. In this way speeds were obtained down to about 2 revs. per minute, and after a short preliminary run it would keep quite constant for as long as required. Even lower speeds could have been obtained by wasting more power on the electrical control. Steadier running can be obtained at these very low speeds when the bearings are cold; a preliminary run at full speed made it almost impossible to get a steady low speed at all. Probably the oil became too thin when warmed by the high-speed run to lubricate the bearings properly at the very low speed. The steadiness could be increased by increasing the electrical braking torque and using more power, but it was considered desirable to limit the current taken from the cells in the interests of greater constancy of the meter current derived from the same cells, and so as to avoid having to employ those cells from which the meter shunts were supplied. It was quite curious to watch the machine crawling round at 2 or 3 revs. per minute, especially when the alternator was short-circuited as a single-phase machine. The rotation then took place in jerks as the conductors passed between the poles. When each of the six phases was short-circuited on itself the braking effect was uniform.

The copper plates were placed in the voltameter after the readings had been taken, the speed of the switch adjusted, and everything ready for a start. As quickly as possible after the current was switched off, the cathodes were removed from the solution and washed by dipping in tap water and then in distilled water, from which they were taken one at a time, dried in blotting paper, and then in an electric oven. In this way the deposits were always bright and gave an excellent surface for the next experiment. The utmost despatch was required until the plates were immersed in the distilled water. If they were partly removed from the electrolyte in order to remove the nuts, the part exposed to the air, even if only for half a minute, would be appreciably oxidised. The value used for the electrochemical equivalent was 1·182 grams per ampere-hour, which agreed with the calibration of the Kelvin balance.

A complete calibration of the meters with steady load was made before commencing the variable load tests, and steady load tests at 5 and 10 amperes were interspersed at intervals. All the experiments were made with the room temperature between 55° F. and 63° F., but in only a few of them did it differ from 60° F. by more than 2° F., and in practically all the experiments of the second series it was found possible to keep the room temperature between 60° F. and 61° F.

Results of the Experiments.

It must be remembered that the experiments were devised so as to magnify any variable load peculiarities which might exist in order to make certain of detecting them. Consequently the errors which are likely to arise in actual use are very much smaller than those shown by the curves. Again, when comparing the results with different makes it is necessary to bear in mind that all are not comparable in point of price, being intended for different services, and that Nos. 1, 16, and 17 are 50-ampere meters, No. 18 a 25-ampere meter, and the rest 10-ampere meters. In other words, these four were run at a much smaller load compared with their rating than the others, which would magnify their solid friction effects and diminish their fluid friction ones. Further, it was necessary to open the cases of Nos. 2, 3, 6, 7, and 18 for each reading in order to get at the wheel scales. These ones were therefore subject to a greater risk of getting dusty and damaged inside than the others.

The results of the experiments are plotted in Figs. 8 to 13, in which they are grouped according to their type. In these figures the ordinate is the "correcting factor" or number by which the record has to be multiplied to make it agree with the rate at which the meter runs on a steady load of 10 amperes. They are plotted downwards so as to make the curve rise when the meter record is high and fall when it is low. It will be seen that these curves are in general agreement with the theory but that one or two discrepancies arise.

Mercury Meters.—The results for the old-type Ferranti meter are given in Fig. 8. It will be noticed that the error approaches, but does not quite reach, the correcting factor of $\frac{1}{2}$ which would apply to the ideal fluid friction meter on this load. The difference is due to the friction of the spindle and counting train, and at full load it would probably be much smaller. The drop in the error with the higher load frequencies is not accounted for by the theory of the meter, and it occurs in all the mercury meters tested. It may be due in part to a change in the form-factor of the load caused by sparking at the switch, and by the finite rate of growth of the current. It was noticed that sparking was much more vivid at the higher speeds, partly because the switch is then attempting to stop the current more quickly and partly also because the tips of the brushes were much hotter owing to friction and greater spark frequency. The spark thus lasted a longer fraction of each revolution at the higher speeds and so smoothed out the wave

more and more as the speed was raised. The Kelvin balance readings, however, do not quite bear this out, but they were not quite certain owing to variations in the contact resistance. Probably most of the effect is caused by the reduction of the driving torque owing to the eddy currents induced in the body of the magnets by the changes of the main current.

The next diagram (Fig. 9) shows tests of Hookham and modern Ferranti meters. The consistency of the latter is most remarkable, none of the points for either of the two meters on the full-load test

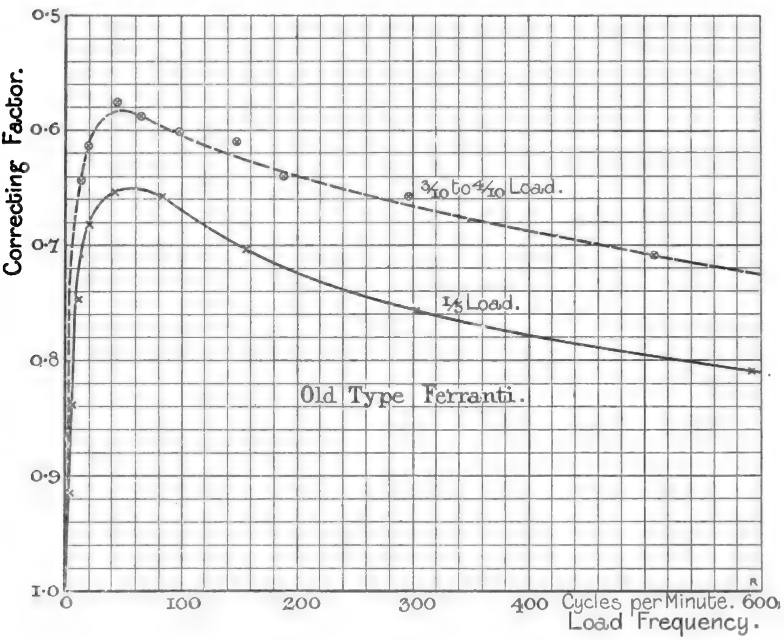


FIG. 8.—Experimental Results for Old-type Ferranti Meter. (No. 17.) (Fluid Friction Meter.)

(second series) deviating by more than three parts in a thousand from the smooth curve drawn through their mean. The discrepancy of the readings for one meter from a smooth curve drawn through its own points is not more than one part in a thousand. The other series does not give such consistent results owing to the variation of the maximum load. It will be noticed that the solid friction makes the meters record too little when the load frequency is small.

No. 18 shows a very large amount of fluid friction, especially as it was well under full load even in the first series. It is, however, an obsolete type, having been superseded by No. 1, which is much better.

No. 1 is a 50-ampere meter, and if tested at full load would probably show an error at least as great as Nos. 13 and 14.

Commutator Ampere-hour Meters.—Theory indicates that with a load of the type used, constant solid friction gives a constant error on the slow side for all load frequencies above that at which the rotor just stops each cycle; below that the error gradually diminishes to zero (see Fig. 2). The actual curves of Fig. 10 differ somewhat from this. Nos. 6 and 7, which may be taken as typical of this type, show a larger

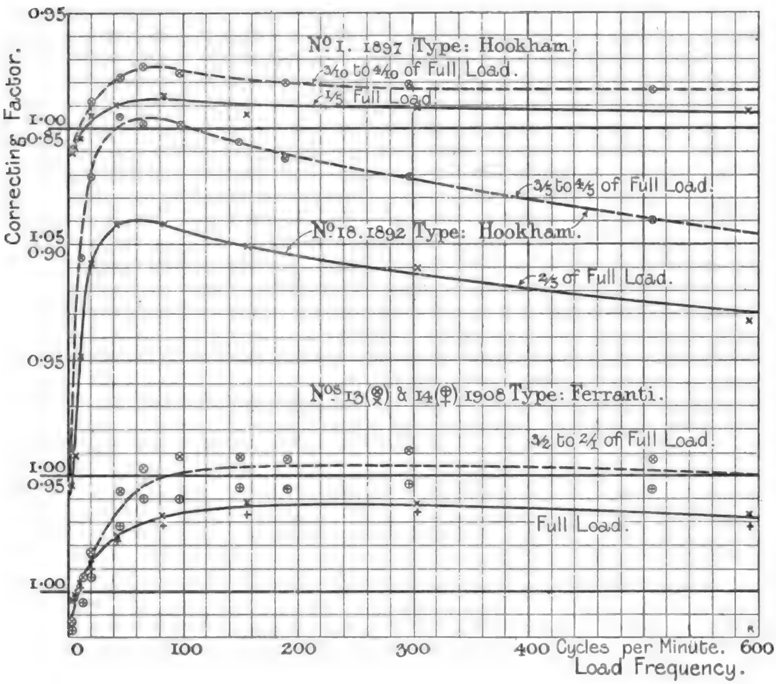


FIG. 9.—Experimental Results for Eddy Brake Mercury Meters.

error at low frequency, which is caused by the increase of solid friction, which is neglected in the theory. At the higher load frequencies the meter speed does not oscillate much from the mean, but at the lower frequencies the rotor stops, or nearly does so, every cycle, and so the greater friction at low speeds comes into play. The irregularities of some of the points for Nos. 6 and 7 may be errors of reading, as the position of the gears made wheel scales very awkward to use. Some of them may also be due to the intrusion of dust particles, and variations in the fixing of the cover, which came very close to the disc.

The results for meters Nos. 4 and 5, which are given on the same diagram and also on Fig. 12, agree more nearly with the theoretical deduction that the error should be zero at zero frequency. But the readings are so erratic that the later part of the curve for No. 5 on Fig. 12, which is drawn to a smaller scale, is only guess-work, while that for No. 4 goes off the paper altogether on Fig. 10. From the curves for these meters on Fig. 12 it will be seen that the error increases with the frequency up to a certain point and then diminishes,

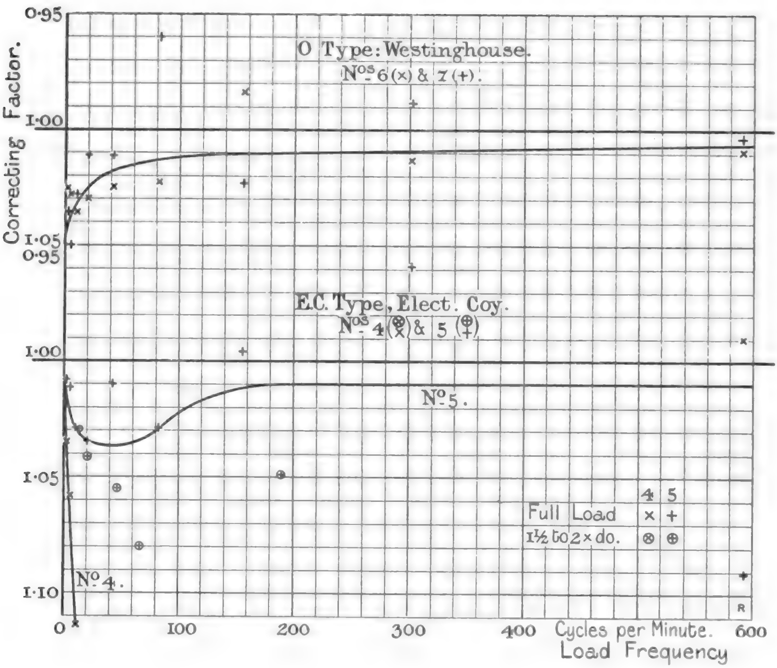


FIG. 10.—Experimental Results for Commutator Ampere-hour Meters. (Eddy Brake Meters with Solid Friction.)

the maximum error for No. 4 being very large. No. 5 only shows traces of the same phenomenon at full load, but they are more distinct when it is overloaded. The brushes on these meters are carried on a rocking arm whose position is varied with the current, and the trouble is probably due to oscillations of this arm with the pulsations of the load, and the effect is greatest when the condition of resonance is attained. The meters tested out all right with steady load after the variable load tests were over. These meters had cyclometer dials in which the reading could be estimated to $\frac{1}{1000}$ unit, and they were tested without breaking the makers' seals.

Commutator Watt-hour Meters (*Thomson Type*).—Fig. 11, which gives the results for three types of energy meter, shows the same effect of increasing solid friction with diminishing rotor speed. All of them show that the solid friction is over-compensated when running, with the result that they record too much on variable loads. The fact that they are over-compensated is also confirmed by the steady load characteristic. However, the error is small in all of them, especially for No. 16, which is of the switchboard type and is the most expensive meter of the lot. The small error is particularly good seeing that it was a

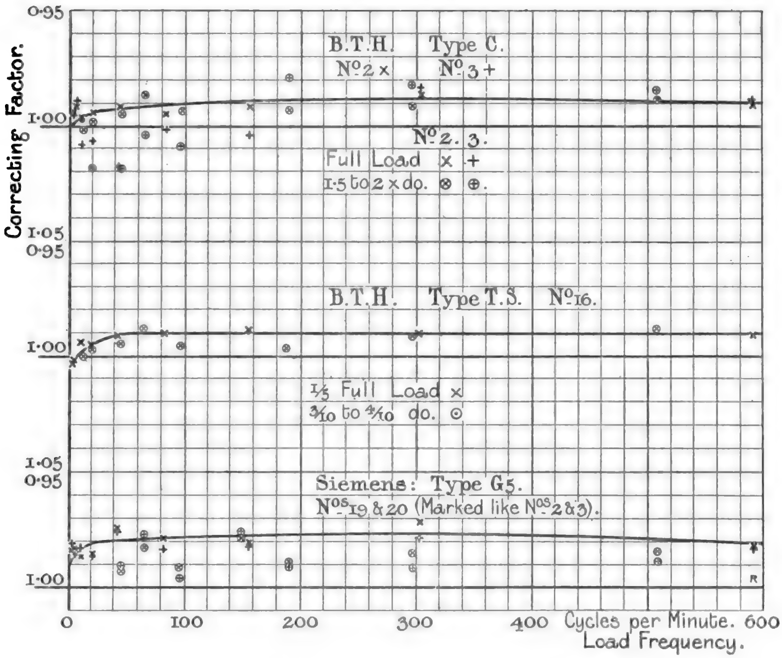


FIG. 11.—Experimental Results for Commutator Energy Meters. (Eddy Brake Meters with Compensated Solid Friction.)

50-ampere meter tested at 10 amperes. It will be seen that the experiments confirm the conclusion that this error is less with greater loads.

All the meters in this group could be improved by readjusting the compensating coil, and the author would suggest that this should be set so that the steady load characteristic is level from, say, one-quarter to three-quarters' load. The meter would then require a rather greater starting current than with the usual adjustment, but, since this type of meter is not used on circuits which are liable to be running on light loads for long times, the overall accuracy would be increased.

Oscillating Meters.—One of the types of meter for which the results are given in Fig. 12 has an armature which oscillates between two stops instead of rotating continuously about its axis. This has the advantage that flexible strips can be employed instead of brushes and a commutator so as to avoid the various troubles to which the latter give rise. At each end of the swing a contact is made by which the dials are electrically operated. The same mechanism also operates a reversing switch in the shunt circuit so as to send the armature back to the other stop. The

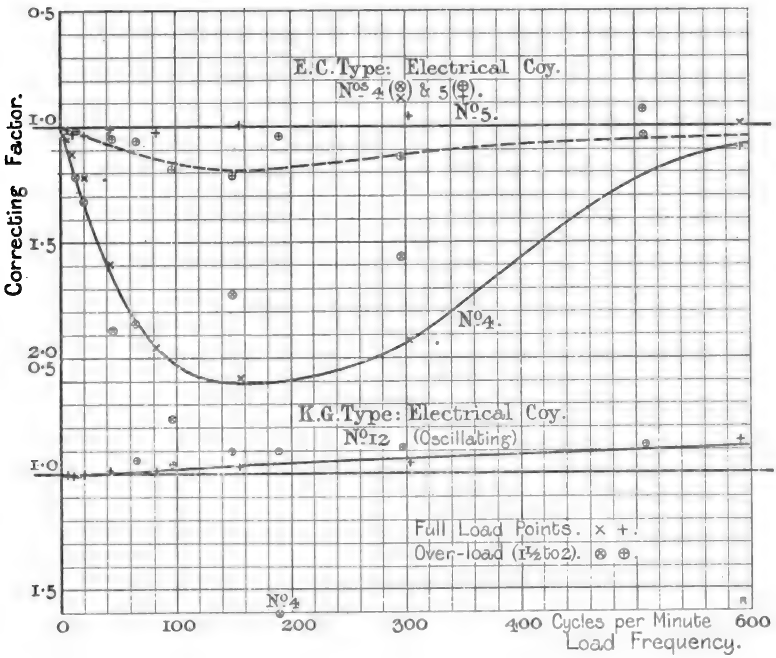


FIG. 12.—Experimental Results for Eddy Brake Meters with Special Features. (Small Scale.)

Nos. 4 and 5 are ampere-hour meters with brushes on a rocking arm, and with spiral commutator segments.
Nos. 11 and 12 have an oscillating armature with electrical counting mechanism and reversing switch for shunt.

only friction acting on the armature is therefore that of its own pivots, which is compensated in the usual manner, but the oscillation seems to introduce difficulties of its own. The errors found in the two examples tested, both on steady load and on variable load, are greater than is usual for a watt-hour meter.

Clock Meters.—Fig. 13 shows the results of the second series of tests only on three of the well-known Aron clock meters. It will be noticed

that large errors may arise when the frequency of the load is the same as that of the pendulums. This phenomenon is exhibited over a very narrow range of load frequency, beyond which the meters are remarkably accurate. In order to detect the effect at all, considerable care is required in adjusting the speed of the switch to the proper value and in keeping it at it, but when once the right frequency is obtained a few minutes' observation of the pendulums will show that something unusual is happening. The amplitude of the swing of the pendulums changes

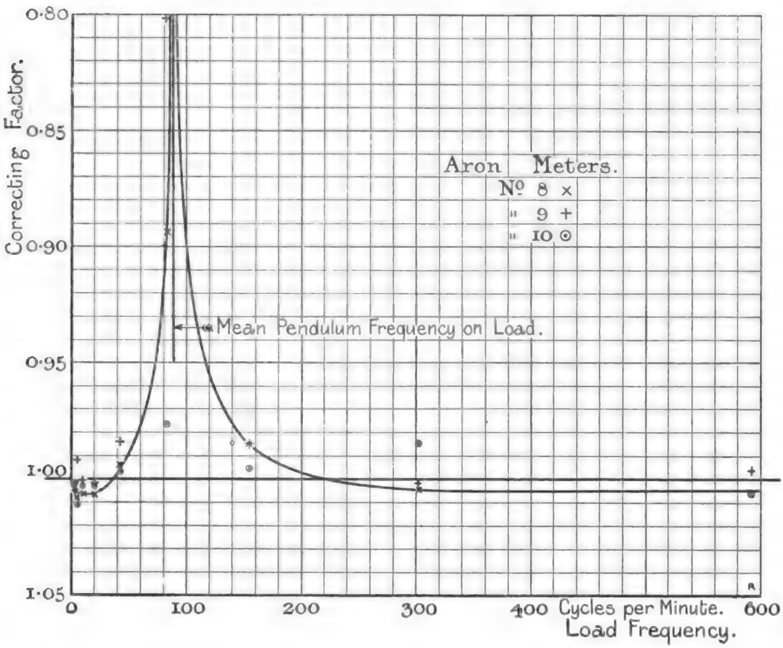


FIG. 13.—Experimental Results for Aron Clock Meters.

rapidly through a wide range, and visible alterations take place in its frequency while doing so.

Owing to the small range over which it happens, this irregularity is of no practical importance on ordinary variable loads. This was proved by experiments made by the author at the Devonport District Tramways switch-house. Standard B.T.H. and Aron meters of 200-ampere size, known to be in substantial agreement on steady load, were placed in series with a tramway feeder whose load was within their range. Readings were taken hourly during the first day, and daily for some time afterwards. At first the Aron meter ran very slightly faster than the B.T.H., but after some rather heavy traffic about midday the latter began to recover its position, and by the end of the day the records

agreed within 1½ parts in a thousand, being 734·8 for the Aron and 735·9 for the B.T.H. This close agreement between two meters differing so widely in their construction and principle of action was taken as conclusive proof that neither of them behaved appreciably differently on a tramway load from what they did on steady load. Permanent effects of sudden loads are, of course, not included in this statement; they can always be detected by a steady load test. Such permanent effects were shown during these experiments, for the difference between the daily records increased day by day, showing a considerable change in one or both meters. After some days the B.T.H. meter began to spark, probably due to the entrance of dust through holes in the temporary base-board, and this became so bad as to render a further test of little value.

A steady load test after the first day's run did show that even in that short time the B.T.H. meter was permanently accelerated to a small extent, and it is generally recognised that this type of meter is subject to such changes. The blame is generally put on the permanent magnets, and those of the meter employed in this test were placed inside a thick iron box with the object of shielding them. The author thinks, however, that the coils themselves may be a contributory cause, owing to their being insufficiently rigid in themselves and their supports to withstand without permanent strain the momentary forces of attraction produced by a heavy overload.

General Conclusions.

We may summarise the results of experiment and theory together thus:—

1. Meters whose main control is fluid friction are quite unsuitable for variable loads.
2. Mercury meters run faster than they ought to on variable loads, and in some cases this error may be serious. It is necessary to make tests on each separate type to make certain that the fluid friction is kept within limits. The proportional amount of fluid friction at full load should not exceed four or five times the permissible error at that load.
3. Electricity (ampere-hour) meters of the commutator type generally record low on variable loads, but, except when the load is such as to allow the meter to stop frequently, the errors are the same as on steady loads. The proportional solid friction should not exceed the permissible error.
4. Energy (watt-hour) meters of the commutator type can be made almost dead accurate for variable loads which do not often allow the rotor to come to rest. The compensating coils should be adjusted, not to get the minimum starting current without creeping, but to give a level characteristic above, say, quarter load. When the adjustment is not right the variable load errors are about the same as the steady load ones.

5. The simplest arrangements are the best. Additions made with the object of improving the steady load characteristic may cause serious errors on variable loads.
6. Clock meters in which there is little damping of the pendulums are as accurate on variable as on steady loads except within a small range of load frequency in which resonance effects occur. This type of meter should not be employed on cyclic loads, such as flashing signs, unless the load frequency differs considerably from that of the pendulums (about 80 cycles per minute).

In conclusion, the author wishes to express his thanks to the following firms for their willing co-operation by lending or giving meters for the tests, viz.: Messrs. Aron Electricity Meter, Ltd., British Thomson-Houston Company, Ltd., British Westinghouse Company, Ltd., The Electrical Company, Ltd., Ferranti, Ltd., Siemens Bros. Dynamo Works, Ltd.; and also to the Engineer of the Bristol Corporation Electricity Department (H. Faraday Proctor, Esq.). He would also acknowledge with gratitude his indebtedness to the Governors of the Merchant Venturers' Technical College, Bristol, for the use of the college equipment, and to his research assistants, Mr. James Brander and Mr. D. C. M'Pherson, for their valuable help in carrying out the experiments and in evaluating the functions obtained from the theory.

APPENDIX.

List of Symbols.

P, P_S = Power being metered.

θ = Rotation of rotor since $\mathsf{T} = 0$.

θ_A, θ_D = Rotation during accelerating and decelerating periods.

θ_T = Total rotation.

$\dot{\theta}$ = Angular velocity of rotor.

$\dot{\theta}_S$ = Steady velocity of rotor, corresponding to steady load P_S, at which meter is supposed to be correct.

$\ddot{\theta}$ = Angular acceleration of rotor.

$\mathsf{t}_r, \mathsf{t}_d$ = Resisting and driving torques.

t_{ro} = Solid friction torque, supposed constant at all speeds.

t_{do} = Driving torque when load is off.

$k_{r_1}\dot{\theta}$ = Eddy-current torque at speed $\dot{\theta}$.

$k_{r_2}\dot{\theta}^2$ = Fluid friction torque at speed $\dot{\theta}$.

k_{d_1}, k_{d_2} = Driving torque constants.

K = Moment of inertia of rotor, etc.

T = Time.

T_A, T_D = Accelerating and decelerating periods.

$T_O = K \div k_{r_1}$ = Time taken to stop from any speed with a constant resisting torque equal to the eddy-current torque at that speed.

$$a = \frac{(t_{ro} - t_{do})}{k_{r_1}\dot{\theta}_S} = \frac{\text{Unbalanced solid friction torque}}{\text{Eddy-current torque at speed } \dot{\theta}_S}.$$

$$b = \frac{k_{r_2}\dot{\theta}_S^2}{k_{r_1}\dot{\theta}_S} = \frac{\text{Fluid friction torque at speed } \dot{\theta}_S}{\text{Eddy-current torque at speed } \dot{\theta}_S}.$$

$$x = \frac{T_A}{T_A + T_D} = \frac{\text{Mean load}}{\text{Maximum load}}.$$

Steady-running, Parabolic Law.

Let the resisting torque be—

$$t_r = t_{ro} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2,$$

and the driving torque be—

$$t_d = t_{do} + k_{d_1}P + k_{d_2}P^2,$$

where the three terms correspond respectively to the solid friction, eddy-current, and fluid friction torques.

If the meter is to be accurate at all steady loads, then—

$$P = k\dot{\theta}.$$

Also, when the speed is steady, the resisting and driving torques must be alike. Hence—

$$\begin{aligned} t_{ro} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2 &= t_{do} + k_{d_1}P + k_{d_2}P^2 \\ &= t_{do} + k\,k_{d_1}\dot{\theta} + k^2 k_{d_2}\dot{\theta}^2. \end{aligned}$$

Since this must be true for any value of P, and therefore of $\dot{\theta}$, we get—

$$t_{ro} = t_{do}$$

$$\left.\begin{aligned} k_{r_1} &= k\,k_{d_1} \\ k_{r_2} &= k^2 k_{d_2} \end{aligned}\right\} \therefore k = \frac{k_{r_1}}{k_{d_1}} = \sqrt{\frac{k_{r_2}}{k_{d_2}}}.$$

Steady Load Frictional Errors in Eddy Brake Meters.

In a meter whose driving torque follows a linear law, let the calibration be such as to make it correct with a certain load P_S giving a speed $\dot{\theta}_{S_1}$.

Let another load $\mathsf{P} = x\,\mathsf{P}_s$ and give a speed $\dot{\theta}$.
Then—

$$\mathsf{t}_{do} + k_{d_1}\mathsf{P} = \mathsf{t}_{ro} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2.$$

and—

$$x\left\{\mathsf{t}_{do} + k_{d_1}\mathsf{P}_S\right\} = x\left\{\mathsf{t}_{ro} + k_{r_1}\dot{\theta}_S + k_{r_2}\dot{\theta}_S^2\right\}.$$

$$\therefore \quad (1 - x)\,\mathsf{t}_{do} = (1 - x)\,\mathsf{t}_{ro} - x\,(k_{r_1}\dot{\theta}_S + k_{r_2}\dot{\theta}_S^2) + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2$$

$$\therefore\ 0 = \left\{\frac{(1 - x)(\mathsf{t}_{ro} - \mathsf{t}_{do})}{k_{r_1}\dot{\theta}_S} - x\left(1 + \frac{k_{r_2}\dot{\theta}_S}{k_{r_1}}\right)\right\} + \frac{\dot{\theta}}{\dot{\theta}_S} + \frac{k_{r_2}\dot{\theta}_S}{k_{r_1}}\,\frac{\dot{\theta}^2}{\dot{\theta}_S^2}$$

$$= \left\{(1 - x)\,a - x\,(1 + b)\right\} + \dot{\theta}/\dot{\theta}_S + b\,(\dot{\theta}/\dot{\theta}_S)^2.$$

Hence, the reciprocal correcting factor is—

$$\frac{\dot{\theta}}{x\dot{\theta}_s} = \frac{1}{2bx}\left[-1 + \sqrt{1 + 4bx\left\{1 + a + b - a/x\right\}}\right]$$

$$= \left\{1 + a + b - a/x\right\} - bx\left\{\cdots\right\}^2 + 2b^2x^2\left\{\cdots\right\}^3 -, \text{ etc.}$$

$$= \left\{1 + a + b - a/x\right\} \text{ if } b = 0 \text{ (no fluid friction)}$$

$$= (1 + b) - bx\,(1 + b)^2 + 2b^2x^2\,(1 + b)^3 -, \text{ etc., if } a = 0 \text{ (no solid friction).}$$

Starting and Stopping, Parabolic Law.

The general equation of motion for any case is—

$$0 = \mathsf{K}\ddot{\theta} + \mathsf{t}_r - \mathsf{t}_d,$$

and for a meter with parabolic law, accurate on steady loads, this becomes, while starting—

$$0 = \mathsf{K}\ddot{\theta} + k_{r_1}(\dot{\theta} - \dot{\theta}_S) + k_{r_2}(\dot{\theta}^2 - \dot{\theta}_S^2).$$

$$= \mathsf{T}_0\,\dot{\theta}'\ddot{\theta} + \dot{\theta}_S\,\dot{\theta} + b\,\dot{\theta}^2 - (1 + b)\,\dot{\theta}_S^2.$$

Starting from zero and from rest, the solution of this is—

$$\theta = \mathsf{T}\dot{\theta}_s - \frac{1}{b}\mathsf{T}_0\dot{\theta}_s \log\frac{(1 + 2b)}{\left\{(1 + b) + b\,\epsilon^{-(1+2b)\mathsf{T}/\mathsf{T}_0}\right\}}$$

$$\therefore \quad \theta_A = \mathsf{T}_A\,\dot{\theta}_S - \frac{1}{b}\mathsf{T}_0\,\dot{\theta}_S \log\frac{1 + 2b}{1 + b}\ \left\{\text{after several times } \mathsf{T}_0 \text{ has elapsed.}\right.$$

When the load is removed, only the constant component of the driving torque remains, and so—

$$\begin{aligned} 0 &= K\ddot{\theta} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2 \\ &= T_0\dot{\theta}_s\ddot{\theta} + \dot{\theta}_s\dot{\theta} + b\,\dot{\theta}^2. \end{aligned}$$

If we suppose that the steady speed was attained before switching off, the solution is—

$$\theta = \frac{1}{b} T_0 \dot{\theta}_s \log\left\{(1 + b) - b\,\epsilon^{-T/T_0}\right\}$$

$$\therefore \quad \theta_D \doteq \frac{1}{b} T_0 \dot{\theta}_s \log(1 + b) \text{ after several times } T_0 \text{ has elapsed.}$$

If, then, the load is on for a time T_A at least several times T_0, the total rotation is—

$$\begin{aligned} \theta_T = \theta_A + \theta_D &= T_A\dot{\theta}_s\left[1 + \frac{T_0}{b\,T_A}\log\frac{(1+b)^2}{(1+2b)}\right] \\ &= T_A\dot{\theta}_s\left[1 + \frac{T_0}{b\,T_A}\log\left\{1 + \frac{b^2}{1+2b}\right\}\right] \\ &= T_A\dot{\theta}_s\left[1 + \frac{T_0}{T_A}\left\{\frac{b}{(1+2b)} - \frac{b^3}{2(1+2b)^2} + \text{etc.}\right\}\right] \\ &= T_A\dot{\theta}_s \text{ if } b = 0 \text{ (no fluid friction),} \end{aligned}$$

and is infinite if b is infinite (fluid friction control).*

If, however, the accelerating period be short, the speed only reaches the value $m\,\dot{\theta}_s$, instead of $\dot{\theta}_s$, where—

$$m = \frac{(1 + b)\left(1 - \epsilon^{-(1+2b)T_A/T_0}\right)}{\left\{(1 + b) + b\,\epsilon^{-(1+2b)T_A/T_0}\right\}}$$

the differential equation for the deceleration may be written—

$$0 = T_0(m\,\dot{\theta}_s)\ddot{\theta} + (m\,\dot{\theta}_s)\dot{\theta} + (m\,b)\dot{\theta}^2,$$

from which we see that $(m\,b)$ must be substituted for b when $(m\,\dot{\theta}_s)$ is put in for $\dot{\theta}_s$.

This gives for the rotation made while stopping:—

$$\theta_D = T_0\,\theta_s \times \frac{1}{b}\log\frac{\left\{(1 + b)^2 - b^2\,\epsilon^{-(1+2b)T_A/T_0}\right\}}{\left\{(1 + b) + b\,\epsilon^{-(1+2b)T_A/T_0}\right\}}$$

* When b is infinite, T_0 also becomes infinite, for the eddy brake torque is then zero. But T_0/b remains finite, being the time taken to stop from any speed with a constant torque equal to that produced by fluid friction at that speed.

and—

$$\theta_T = T_A\dot{\theta}_S\left[1 + \frac{1}{b}\frac{T_O}{T_A}\log\frac{\{(1+b)^2 - b^2\epsilon^{-(1+2b)T_A/T_O}\}}{(1+2b)}\right]$$

$$= T_A\dot{\theta}_S\left[1 + \frac{1}{b}\frac{T_O}{T_A}\log\left\{1 + \frac{b^2(1-\epsilon^{-(1+2b)T_A/T_O})}{(1+2b)}\right\}\right]$$

$$= T_A\dot{\theta}_S\left[1 + \frac{T_O}{T_A}\left\{\frac{b(1-\epsilon^{-(1+2b)T_A/T_O})}{(1+2b)} - \frac{1}{2}\frac{b^3(1-\epsilon^{-(1+2b)T_A/T_O})^2}{(1+2b)^2} +, \text{etc.}\right\}\right]$$

$$= T_A\dot{\theta}_S \text{ if } b = 0 \text{ (no fluid friction),}$$

and is infinite if b is infinite (fluid friction control).

The product outside the square brackets is what the meter would record if it had no inertia. The content of these brackets is therefore the reciprocal of the correcting factor to be used. It will be noticed that the extra rotation made during deceleration exactly balances the loss during acceleration if there be no fluid friction, but always exceeds it when there is fluid friction. This statement applies whether the load is on long enough to produce the steady speed or not.

In those cases in which the fluid friction is the main term and eddy-current control negligible, b and T_O become very large, and the extra rotation approaches an infinite amount.

Starting and Stopping with Uncompensated Solid Friction.

In the previous case the solid friction was supposed to be so compensated that the meter would be correct on all steady loads. When the solid friction is un- or over-compensated, the starting equations remain unchanged if we suppose the meter to be correct with that particular load, for we may suppose the constant total driving torque to be apportioned off between the different components of the resisting torque at the steady speed.

When stopping, however, we have the additional retarding torque $(t_{ro} - t_{do})$ which we did not have before, giving the equation—

$$0 = K\ddot{\theta} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2 + (t_{ro} - t_{do}).$$

$$= T_O\dot{\theta}_S\ddot{\theta} + \dot{\theta}_S\dot{\theta} + b\,\dot{\theta}^2 + a\,\dot{\theta}_S^2.$$

Hence—

$$\theta = \frac{1}{b}T_O\dot{\theta}_S\log\frac{\{(1+2b)+\sqrt{1-4ab}\} - \{(1+2b)-\sqrt{1-4ab}\}\epsilon^{-\sqrt{1-4ab}\,T/T_O}}{2\sqrt{1-4ab}}$$

$$- \frac{1}{2b}T\dot{\theta}_S\{1-\sqrt{1-4ab}\}$$

$$\dot{\theta} = \frac{\dot{\theta}_S}{2b}\left[\frac{\{1+\sqrt{1-4ab}\}\{(1+2b)-\sqrt{1-4ab}\}e^{-\sqrt{1-4ab}\,T/T_0} - \{1-\sqrt{1-4ab}\}\{(1+2b)+\sqrt{1-4ab}\}}{\{(1+2b)+\sqrt{1-4ab}\} - \{(1+2b)-\sqrt{1-4ab}\}e^{-\sqrt{1-4ab}\,T/T_0}}\right]$$

These equations hold only until the meter stops ($\dot{\theta} = 0$), which occurs in a time—

$$T_D = \frac{T_0}{\sqrt{1-4ab}}\log\frac{\{1+\sqrt{1-4ab}\}\{(1+2b)-\sqrt{1-4ab}\}}{\{1-\sqrt{1-4ab}\}\{(1+2b)+\sqrt{1-4ab}\}}$$

$$= \frac{T_0}{\sqrt{1-4ab}}\log\frac{\{(1+2a)+\sqrt{1-4ab}\}}{\{(1+2a)-\sqrt{1-4ab}\}}$$

which may be inserted above to get θ_D.

Hence the total record in this case is—

$$\theta_T = \theta_A + \theta_D$$

$$= T_A\dot{\theta}_S\left[1 - \frac{T_0}{bT_A}\left\{\log\frac{(1+2b)}{(1+b)} - \log\frac{\{(1+b)+\sqrt{1-4ab}\}}{\{1+\sqrt{1-4ab}\}} + \frac{\{1-\sqrt{1-4ab}\}}{2\sqrt{1-4ab}}\log\frac{\{(1+2a)+\sqrt{1-4ab}\}}{\{(1+2a)-\sqrt{1-4ab}\}}\right\}\right]$$

On short runs from rest the speed only rises to the value $m\,\dot{\theta}_S$, where m has the same value as in the previous case. In the same way as before, it can be shown that in the equations for the deceleration we must put $(m\,\dot{\theta}_S)$ for $\dot{\theta}_S$, $(m\,b)$ for b, and (a/m) for a, giving—

$$\theta_D = T_0\dot{\theta}_S\left[\frac{1}{b}\log\frac{\{1+2mb+\sqrt{1-4ab}\}}{\{1+\sqrt{1-4ab}\}} - \frac{\{1-\sqrt{1-4ab}\}}{2b\sqrt{1-4ab}}\log\frac{\{1+2a/m+\sqrt{1-4ab}\}}{\{1+2a/m-\sqrt{1-4ab}\}}\right]$$

and, $\theta_T = \theta_A + \theta_D$

$$= T_A\dot{\theta}_S\left[1 - \frac{T_0}{bT_A}\left\{\log\frac{(1+2b)}{(1+b)} - \log\frac{\{1+2mb+\sqrt{1-4ab}\}}{\{1+\sqrt{1-4ab}\}} + \frac{\{1-\sqrt{1-4ab}\}}{2\sqrt{1-4ab}}\log\frac{\{1+2a/m+\sqrt{1-4ab}\}}{\{1+2a/m-\sqrt{1-4ab}\}}\right\}\right]$$

HIGH-FREQUENCY RECTANGULAR-WAVE LOAD, PARABOLIC LAW.

Let the load be a periodic one, on for the fraction x of each cycle, and off for the remainder. Also let the frequency of the load be high enough to make the variations of the speed throughout a cycle negligible. Then, if $\dot{\theta}$ be the actual speed of the meter, and $\dot{\theta}_s$ what it would be if the same load were kept steadily on, we have—

$$\text{Mean driving torque} = \bar{t}_d = \frac{1}{T}\int_0^T \{t_{ro} + k_{r_1}\dot{\theta}_s + k_{r_2}\dot{\theta}_s^2\}\, dT.$$

$$= t_{ro} + x\, k_{r_1}\dot{\theta}_s + x\, k_{r_2}\dot{\theta}_s^2.$$

Also—

$$\bar{t}_d = \bar{t}_r = t_{ro} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2.$$

Hence—

$$0 = k_{r_2}\dot{\theta}^2 + k_{r_1}\dot{\theta} - x\,\dot{\theta}_s(k_{r_1} + k_{r_2}\dot{\theta}_s)$$
$$= b\,\dot{\theta}^2 + \dot{\theta}_s\dot{\theta} - x\,\dot{\theta}_s^2(1 + b)$$

and so the reciprocal of the correcting factor is—

$$\frac{\dot{\theta}}{x\,\dot{\theta}_s} = \frac{1}{2bx}\{-1 + \sqrt{1 + 4bx(1+b)}\}$$

$$= (1+b)\{1 - bx(1+b) + 2b^2x^2(1+b)^2 -, \text{etc.}\}$$
$$= (1+b) \text{ if } bx \text{ be very small.}$$

This is the same as we have already found for a steady load when there is no solid friction, and so this particular case gives the same speed as a steady load equal to the mean, if the fluid friction with steady loads is uncompensated. If the latter be fully compensated by a quadratic term in the driving torque, as assumed above, the steady load characteristic will be level, and the variable load error that which is given by the above equation and in the table.

RECIPROCAL CORRECTING FACTORS FOR HIGH-FREQUENCY RECTANGULAR-WAVE LOAD WITH $x = \frac{1}{4}$ FOR METER WITH PARABOLIC LAW.

b	0·000	0·010	0·025	0·050	0·100	0·500	1·000	∞
$\dot{\theta}/x\dot{\theta}_s$	1·000	1·007	1·019	1·036	1·071	1·292	1·464	2·000

There is, however, another way in which the fluid friction may be compensated so long as it is less than the driving torque. The latter may be left to follow the linear law, and the braking flux reduced so as to diminish the eddy-current torque by an amount equal to the fluid friction. That is, k_{r_1} is reduced to k'_{r_1} when the load is on, and so—

$$\mathbf{t}_d = \mathbf{t}_{ro} + k_{r_1}\dot{\theta}_S = \mathbf{t}_{ro} + k'_{r_1}\dot{\theta}_S + k_{r_2}\dot{\theta}_S^2.$$

$$\therefore \quad \frac{k'_{r_1}}{k_{r_1}} = 1 - \frac{k_{r_2}\dot{\theta}_S}{k_{r_1}} = (1 - b).$$

Also, under the variable load—

$$\bar{\mathbf{t}}_d = \mathbf{t}_{ro} + x\,k_{r_1}\dot{\theta}_S.$$

$$\bar{\mathbf{t}}_r = \mathbf{t}_{ro} + \left\{x\,k'_{r_1} + (1 - x)\,k_{r_1}\right\}\dot{\theta} + k_{r_2}\dot{\theta}^2.$$

$$\therefore \quad 0 = k_{r_2}\dot{\theta}^2 + \left\{x\frac{k'_{r_1}}{k_{r_1}} + (1 - x)\right\}k_{r_1}\dot{\theta} - x\,k_{r_1}\dot{\theta}_S.$$

$$= b\,\dot{\theta}^2 + (1 - b\,x)\,\dot{\theta}\,\dot{\theta}_S - x\dot{\theta}_S^2.$$

$$= (\dot{\theta} - x\,\dot{\theta}_S)(b\,\dot{\theta} + \dot{\theta}_S)$$

Hence—

$$\dot{\theta} = x\,\dot{\theta}_S$$

and there is no error in this case.

This is thus a better method of compensation, but usually both $\mathbf{t}_r$ and $\mathbf{t}_d$ are altered by changing the distribution of a constant total flux between the motor and brake discs. The fluid friction error is then intermediate between those found. In many types of mercury meter, the motor disc acts partly as a brake disc as well, and so that part of the eddy-current torque is increased by the compensating coil. If the braking is more or less evenly divided between the discs, the total eddy-current torque may be *increased* instead of being diminished, although to a less extent than the driving torque. In such a case, the fluid friction effects on variable load are magnified.

In a fluid friction meter, the middle term of the first of the above quadratic equations disappears, and b becomes so large as to be practically equal to $(1 + b)$. So we get—

$$\frac{\dot{\theta}}{x\,\dot{\theta}_S} = \frac{1}{\sqrt{x}} \text{ for a fluid friction meter.}$$

The correcting factor in this case is thus $\sqrt{x}$.

High-frequency Rectangular-wave Load, Uncompensated Solid Friction.

In this case the driving torque is:—
During a fraction x of the time—

$$t_{ro} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}_S^2,$$

and during the remaining $(1 - x)$—

$$t_{do}.$$

Hence, the mean driving torque is—

$$\bar{t}_d = (1 - x)\,t_{do} + x\,t_{ro} + x(k_{r_1}\dot{\theta}_S + k_{r_2}\dot{\theta}_S^2),$$

and the resisting torque is—

$$\bar{t}_r = t_{ro} + k_{r_1}\dot{\theta} + k_{r_2}\dot{\theta}^2.$$

$$\therefore\ 0 = k_{r_2}\dot{\theta}^2 + k_{r_1}\dot{\theta} + (1 - x)(t_{ro} - t_{do}) - x(k_{r_1}\dot{\theta}_S + k_{r_2}\dot{\theta}_S^2),$$
$$= b\,\dot{\theta}^2 + \dot{\theta}\,\dot{\theta}_S + \{(1 - x)\,a - x(1 + b)\}\,\dot{\theta}_S^2.$$

Hence, the reciprocal of the correcting factor is—

$$\frac{\dot{\theta}}{x\,\dot{\theta}_S} = \frac{1}{2\,b\,x}\left[-1 + \sqrt{1 + 4b\,x\{1 + a + b - a/x\}}\right]$$
$$= \{1 + a + b - a/x\}\,[1 - b\,x\,\{1 + a + b - a/x\}$$
$$+ 2\,b^2\,x^2\,\{\cdots\}^2 -, \text{etc.}]$$
$$\doteq \{1 + a + b - a/x\} \text{ if } b\,x \text{ be small.}$$
$$= \{1 + a - a/x\} \text{ if } b = 0 \text{ (no fluid friction).}$$

For the fluid friction meter the equation gives—

$$\frac{\dot{\theta}}{x\,\dot{\theta}_S} = \frac{\sqrt{x - (1 - x)\,a/b}}{x} = \frac{\sqrt{1 - (1/x - 1)\,a/b}}{\sqrt{x}},$$

where a/b is the proportion of the unbalanced solid to the fluid friction at the speed $\dot{\theta}_S$.

Moderate-frequency Rectangular-wave Load. Effect of Uncompensated Solid Friction on Eddy Brake Meter.

We have studied the general problem in the two extreme cases where the load frequency is so low that the rotor gets up full speed and stops dead every cycle, and where it is so high that the variations in

the rotor speed in one cycle can be neglected. The intermediate case is much more difficult to deal with, but even the general problem is still soluble.

However, owing to the cumbrous equations it gives (the author has found a whole page necessary for writing down parts only of the expressions obtained, even when using an abbreviated tabular notation), it is more convenient to deal with solid and fluid friction separately.

When there is no fluid friction ($b = 0$), the differential equations become—

$$\text{During acceleration: } 0 = T_0 \ddot{\theta} + \dot{\theta} - \dot{\theta}_S.$$
$$\text{During deceleration: } 0 = T_0 \ddot{\theta} + \dot{\theta} + a\,\dot{\theta}_S.$$

If $\dot{\theta}_1$, $\dot{\theta}_2$ be the rotor speeds at the beginning of the accelerating and decelerating periods respectively, they must also be the speeds at the ends of the decelerating and accelerating periods when a steady state is reached.

The solutions with these terminal conditions are—

$$\text{Acceleration: } \theta = \dot{\theta}_S T - (\dot{\theta}_S - \dot{\theta}_1) T_0 (1 - \epsilon^{-T/T_0}).$$
$$\text{Deceleration: } \theta = (\dot{\theta}_2 + a\,\dot{\theta}_S) T_0 (1 - \epsilon^{-T/T_0}) - a\,\dot{\theta}_S T.$$

Differentiating these, we get the velocities—

$$\text{Acceleration: } \dot{\theta} = \dot{\theta}_S - (\dot{\theta}_S - \dot{\theta}_1)\,\epsilon^{-T/T_0}.$$
$$\text{Deceleration: } \dot{\theta} = (\dot{\theta}_2 + a\,\dot{\theta}_S)\,\epsilon^{-T/T_0} - a\,\dot{\theta}_S.$$

Inserting T_A in the first and T_D in the second, we get equations from which $\dot{\theta}_1$ and $\dot{\theta}_2$ can be found, viz.:—

$$\dot{\theta}_2 = \dot{\theta}_S (1 - \epsilon^{-T_A/T_0}) + \dot{\theta}_1 \epsilon^{-T_A/T_0}.$$
$$\dot{\theta}_1 = \dot{\theta}_2 \epsilon^{-T_D/T_0} - a\,\dot{\theta}_S (1 - \epsilon^{-T_D/T_0}).$$
$$= \dot{\theta}_S (1 - \epsilon^{-T_A T/0})\,\epsilon^{-D/T_0} + \dot{\theta}_1 \epsilon^{-T_A/T_0} \epsilon^{-T_D/T_0} - a\,\dot{\theta}_S (1 - \epsilon^{-T_D/T_0})$$

$$\therefore \quad \dot{\theta}_1 = \frac{\dot{\theta}_S \left\{ (1 - \epsilon^{-T_A/T_0})\,\epsilon^{-T_D/T_0} - a\,(1 - \epsilon^{-T_D/T_0}) \right\}}{(1 - \epsilon^{-T_A/T_0}\,\epsilon^{-T_D/T_0})}$$

and—

$$\dot{\theta}_2 = \frac{\dot{\theta}_S \left\{ (1 - \epsilon^{-T_A/T_0}) - a\,(1 - \epsilon^{-T_D/T_0})\,\epsilon^{-T_D/T_0} \right\}}{(1 - \epsilon^{-T_A/T_0}\,\epsilon^{-T_D/T_0})}$$

If these values be put in the equations for θ, as well as the total

times (T_A or T_D) for which each applies, it will be found that the total rotation per cycle can be expressed in the simple form—

$$\theta_T = \dot{\theta}_S(T_A - a\,T_D),$$

and so—

$$\frac{\theta_T}{T_A\dot{\theta}_S} = \{1 - a\,(1 - x)/x\} = (1 + a - a/x).$$

since—

$$x = T_A/(T_A + T_D).$$

This applies to all frequencies not less than that which just allows the rotor to stop. Below that, the starting and stopping equations would have to be employed, using the actual time T_A for the accelerating equation.

The result we have just obtained agrees with those already found for the high-frequency load and for the steady load. It is remarkable that the terms involving the frequency should all disappear, and so the effect is the same for all frequencies above the limit mentioned, and hence also for all wave-forms, for any wave can be built up of a series of rectangular waves. The proportional error gradually falls to zero below this limit, because of the diminishing importance of terminal effects as the time of steady running is increased.

Moderate-frequency Rectangular-wave Load. Effect of Fluid Friction on Eddy Brake Meter.

When there is appreciable fluid friction, but no unbalanced solid friction, the equations for the eddy brake meter become—

During acceleration : $0 = T_0\dot{\theta}_S\ddot{\theta} + \dot{\theta}_S\dot{\theta} + b\,\dot{\theta}^2 - (1 + b)\,\dot{\theta}_S^2.$

During deceleration : $0 = T_0\dot{\theta}\,\ddot{\theta} + \dot{\theta}\,\dot{\theta} + b\,\dot{\theta}^2.$

The solutions for the rotation are—

Acceleration : $$\theta = T\dot{\theta}_S + \frac{1}{b}T_0\dot{\theta}_S \log \frac{\{(1 + b) + b\,\dot{\theta}_1/\dot{\theta}_S\} + b\,(1 - \dot{\theta}_1/\dot{\theta}_S)\,\epsilon^{-(1+2b)T/T_0}}{(1 + 2b)}$$

Deceleration : $$\theta = \frac{1}{b}T_0\dot{\theta}_S \log\{1 + b\,(1 - \epsilon^{-T/T_0})\,\dot{\theta}_2/\dot{\theta}_S\}$$

and the velocities are—

Acceleration :

$$\dot{\theta} = \dot{\theta}\left[1 - \frac{(1 + 2b)\,(1 - \dot{\theta}_1/\dot{\theta}_S)\,\epsilon^{-(1+2b)T/T_0}}{\{(1 + b) + b\,\dot{\theta}_1/\dot{\theta}_S\} + b\,(1 - \dot{\theta}_1/\dot{\theta}_S)\,\epsilon^{-(1+2b)T/T_0}}\right]$$

Deceleration :

$$\dot{\theta} = \frac{\dot{\theta}_2\,\epsilon^{-T/T_0}}{\{1 + b\,(1 - \epsilon^{-T/T_0})\,\dot{\theta}_2/\dot{\theta}_S\}}$$

Proceeding exactly as before, but with the difference that the equations for $\dot{\theta}_1$ and $\dot{\theta}_2$ are quadratics, and that a long factor only cancels out after these are solved, we get for the reciprocal correcting factor—

$$\frac{\theta_T}{T_A \dot{\theta}_S} = \left[1 + \frac{1}{b}\frac{T_O}{T_A} \log \left\{ \frac{\left[\left\{ (1+b)^2 - b^2 \epsilon^{-T_A/T_O} \right\} - \left\{ b^2 - (1+b)^2 \epsilon^{-T_A/T_O} \right\} \epsilon^{-T_D/T_O} \right]}{2(1+2b)} \right. \right.$$
$$\left. \left. + \sqrt{ \left[\frac{ \left\{ (1+b)^2 - b^2 \epsilon^{-T_A/T_O} \right\} - \left\{ b^2 - (1+b)^2 \epsilon^{-T_A/T_O} \right\} \epsilon^{-T_D/T_O} }{2(1+2b)} \right]^2 - \epsilon^{-T_A/T_O} \epsilon^{-T_D/T_O} } \right\} \right]$$

DISCUSSION.

Mr. Trotter.

Mr. A. P. TROTTER: We have before us this evening two papers of an extremely valuable character containing practical and theoretical information. I must say that I attach a great deal more importance in this case to the practical information than to the theoretical. I do not wish for a moment to disparage the value of theory either in these papers or in any other place, but I do not think that this important question of the suitability of meters for steady currents and for traction could possibly be settled by any amount of theory. This question has gradually become more and more important, and I have felt a rather serious responsibility about it. Strictly speaking, this responsibility is not an official one, because the large number of types of meters—I think fifty-three—which have been approved by the Board of Trade under the Electric Lighting Acts are all moderate-sized meters, chiefly for domestic use. We have had hardly one type of large meter submitted for approval, and the meters in question are mainly much larger than those that have received such approval. But still, although the Board of Trade approval of the meters has not been therefore officially challenged, I and my assistants have felt very uneasy upon the subject, because there have been complaints that certain meters were good enough with steady current loads, but perfectly unsuitable for traction. Those that were sent to us for verification were naturally tested upon steady loads, and the suggestion was that our tests were not worth anything because the meters were used upon tramways, and we had not got a tramway. If we had a tramway, what could we have done with it? It is rather difficult to say. The only test that we could make was upon a steady load. But the matter could not be left there. It was an important matter for this reason, that very large sums of money are dependent upon a difference of 1 or 2 per cent. in such cases. Disputes have arisen, and the matter has been tried in the courts, and I felt that this question must be settled practically. Intui-

tively I always felt that a good meter was going to be all right, but I was not convinced rationally. As far as reasons go, I never came across a sound reason against it, but there are fairly good theoretical reasons to show that a good meter might behave badly on a tramway load, and after inquiring from the engineers of traction stations we generally found plenty of reason for the misbehaviour; for instance, large electric lighting mains passing just behind the meters, taking an entirely different load from the tramway, and I must say unfair treatment of meters. Meters are sometimes sent to us to test without being screwed up and with things broken, and so on in a perfectly reckless way. That again was another reason. I have always recommended—and there I differ a little with the remark made in the paper—a good travelling meter. Meters of several different types can be specially arranged for travelling. They are not supposed to be unusually accurate meters, but simply portable meters. They can be put in series with the traction load and sent back for verification, and I think fairly good tests can be made in that way. Having felt very uneasy on the subject, as I said some time ago, I have gradually been putting the matter on one side, because I have heard of good results elsewhere. There was some trouble in the North at one time, but I have since heard that they have been getting two totally different types of meters agreeing well within 1 per cent. on tramway load. There is another place, Croydon, where there was trouble at one time; we looked into the matter and made various tests and suggestions, and I believe the comparison between two types of meters there has been perfectly satisfactory. It will not do to put in three meters all of the same type and say "We will take the best two." I think there is some little room for error there. But I do think that if two meters of different types are taken, and they read well within 1 per cent., this can hardly be accidental. And that is really the basis of these papers—that different types of meters are found to read correct on these varying loads. The matter has been a source of anxiety and uncertainty, but I feel that these two papers now settle the question once and for all. There can now be no doubt that good meters are perfectly suitable for traction or for variable load, although they may be tested in the laboratory upon steady load. The papers that we have heard to-night will, I think, inspire very great confidence. The work that has been carried out by Mr. Melsom and his colleague is just the kind of work for which the National Physical Laboratory is so well suited, as far as practical work goes—work, valuable to the general industry, which it is worth nobody's while to carry out. The last test mentioned in Professor Robertson's paper was a practical one, and the result agrees with that of Mr. Melsom. As far as the theory goes, I feel that his conclusions are not quite so sound. The question of fluid friction is a difficult one. To condemn mercury meters in the general way that he appears to do is rather surprising, and I would refer him or anybody else to a short article on "Fluid Friction" *—21 years ago—upon the fluid Mr. Trotter.

* *Electrician*, vol. 27, p. 190, 1890.

Mr. Trotter. friction of mercury in Professor Perry's meter. Professor Perry's meter, it may be remembered, was a very slow-working mercury meter. It was held by the courts to be under another patent, although obviously it was a totally independent invention. Mercury meters as we know them are extremely good and useful instruments.

Mr. Holden. Mr. S. H. HOLDEN: As representing one of the manufacturers, I want to say how very pleased we are that the National Physical Laboratory have taken up this question of the use of meters on very variable loads. The point has already been brought to our notice by customers, or would-be customers, with regard to using meters on tramway loads. We have always said from theoretical considerations that the meter would be all right, but we have not had the opportunity of carrying out the tests; and, even if we had, they would not have carried anything like the weight that tests made by the National Physical Laboratory do. I suppose the reason there is no curve showing the effect of tilting out of level of meters D and A, and for the effects of stray fields on meters D and G, is because there are practically no appreciable effects to record. With regard to Fig. 3, the voltage curve, if that may be taken as an average specimen, it shows variation of voltage of about 1½ or 2 per cent. up and down. I think tests on the meters with variations of about 2 or 3 per cent., in addition to the tests that Mr. Melsom made, would probably have been useful. With regard to Professor Robertson's paper, some explanation appears to be due. Professor Robertson asked my firm to supply him with meters, but we thought fit at the time to decline his request, because we had already been told that similar tests were to be made at the National Physical Laboratory covering the same ground. I want to mention this because it will no doubt explain why Professor Robertson had to use somewhat old types of Chamberlain and Hookham meters for his tests. The meters appear to have been in very good order and could hardly have been better if the makers had adjusted them immediately beforehand. The 1892 type, however, is really obsolete, and while the 1897 type is not obsolete it is old and not quite so good as our 1908 type. If one of these latter had been available for Professor Robertson it would have shown up better. But I think it will be noticeable that the meter designed by Mr. Hookham so long ago as 1897 does compare exceedingly well with quite modern meters.

Mr. Baker. Mr. C. A. BAKER: My remarks on the subject of meters when discussing the paper contributed by Messrs. Ratcliffe and Moore about twelve months ago are unfortunately, by a clerical error, attributed to some one whose name resembles my own, and since it is unfair to debit him with my opinions, I desire to take advantage of the opportunity afforded me to put the matter right on this occasion. The authors have been fortunate in being able to follow the life of the meters described, during a considerable period; when meters come into my hands for testing they must be reported upon as quickly as circumstances permit, and no further information as to their subsequent behaviour is available.

Mr. Baker.

It is extremely interesting to be able to follow the fortunes of special meters, and to know what happens to them when registering the varying loads of tramway work, such as those described are now doing in the ordinary course at Sutton. I do not in the usual way have very many tramway meters to test; the Tramway Department of the London County Council send me theirs, when purchased, to check for accuracy, but the number is comparatively limited. Quite a large number of meters are, however, now coming into my hands which are used for measuring the supply to electrically illuminated signs—a very similar class of work to that described by the authors. There are a great many of these electric signs all over London. The load is a very variable one, the accounts depending upon the readings of the meters are frequently large, and the opinions of the vendors and purchasers of the energy used are often at variance. It is gratifying to find that the systematic and special tests which the authors have applied to meters working under such conditions prove the meters to be reliable for variable loads, if it is found that they are reliable under the steady load conditions of the ordinary test.

It would be interesting to know something about the dates of the journeys to Tynemouth and elsewhere. The curves given in Figs. 5 to 10 only show the relative dates, and one cannot determine on the other curves, Figs. 11 and 15, whether either of these was plotted immediately after the journey was accomplished. I take it that the 21st October curves shown in Figs. 11, 12, and 13 represent the conditions soon after the journey. If that is so, the journey seems rather to have benefited meters E and C. All of the meters tested in the L.C.C. laboratory have to undergo a journey, and I am often questioned as to whether by removing a meter and taking it to and from the Council's testing station some inaccuracy is not introduced; evidently such suggestions can be safely disregarded, and a good many of the engineers of supply undertakings will feel happier on this point in view of the authors' travelling experiment to Tynemouth without materially affecting the meters. The variations shown in curves 5 and 10 appear to be due in many cases to fickleness and not to the journeys. On page 475 the table which the authors give, showing the very remarkable accuracy and agreement of all these meters, proves that although in themselves they have trifling errors, yet when set to work for a period of three weeks they average out with quite remarkable accuracy. I am very pleased to see that the law of average, which under other circumstances I advocated on a recent occasion, is so evident in this long run. On the question of stray fields the authors say that no very definite information has been published. I am afraid it is too good to hope for anything in the way of definite information on such a very indefinite subject; the information that can be obtained is always of such a variable character that it cannot very well be classified. From observation of the curves the variation caused appears to be about 5 per cent. at quarter load and is always a plus reading; no doubt by arranging the experiments differently a minus error would have been obtained. In this connection I might

Mr. Baker. mention a recent experience when it was found that the position of the iron fender in the test-room made a considerable difference to the result of certain tests: a preliminary test gave results which we could not repeat until the fender was stood on end where it happened to have been placed originally; the effect was due, of course, to a distorted field, a twin brother of the stray field and equally indefinite. The conclusion arrived at was that the particular meters should not be tested or set to work at a less distance apart than 3 ft. It is pretty well known that a certain type of meter was once in the hands of the Board of Trade awaiting their approval; during the wait a large number of the meters were manufactured and calibrated. In due course the Board of Trade approval was obtained; the makers thereupon promptly attached a small iron label stating that the meter was "approved by the Board of Trade." This small iron label sufficiently distorted the field to make it necessary to re-test and re-calibrate the whole of the meters before they were sent out from the works.

The well-known coin test, to prove that a meter has been set up level, is excellent when the inside of the meter can be got at, but it often happens in actual working that a meter is sealed up and there is no possibility of putting a penny or a shilling on the disc in order to observe any rotation due to want of level. Is it too much to ask the manufacturers to put a small spirit bulb on the meter case to afford the necessary indication? From the figures which the authors show for inaccuracy at low loads, such a thing seems to be desirable, the error being always against the supply authority. The authors' temperature coefficients for the sizes of meters they are dealing with in this paper seem to be such as are generally applicable, but for smaller meters, ampere-hour as well as watt-hour meters, the figures vary considerably. The sort of general coefficient that one has in one's mind for small meters is about 0·3 per cent. per °C. of variation of temperature, that is particularly for direct-current meters. With alternating-current meters the temperature effect appears to be very much less. The accompanying table of temperature coefficients (some of which were given me by Mr. Gerhardi, of the Metropolitan Company) is used in the L.C.C. work and may prove useful to others engaged in meter-testing work.

I am very pleased to see that the authors touch on the subject of the suitability of meters for a particular load; that is a point which I also drew attention to in the discussion on Messrs. Ratcliffe and Moore's paper. It often happens that a meter is working for a very large proportion of its life on a very small portion of the load for which it was designed and calibrated: premises are left in charge of caretakers whilst the owners are out of town, during which time a few lamps only are used, but the meter is registering at a fraction of its load, where the error is comparatively large, and under such conditions it is recording unfairly. On the other hand, meters are sometimes working with an overload during the time that the bulk of the registration is effected. The authors suggest that 0·5 per cent. of

accuracy can be obtained with a potentiometer on about 100 seconds' reading. I have adopted 180 seconds, and come within 0·5 Mr. Baker.

Temperature Coefficients Used.

Type.	Capacity in Amperes.	Coefficient per Cent. for 1° C. Rise in Temperature.
Ampere-hour Meters.		
Ferranti	1½ to 50	0·330+
Ferranti	100	0·170+
Ferranti	300	0·056+
Ferranti	700	0·024+
Ferranti	1,000	0·017+
Ferranti	1,200	0·014+
Chamberlain and Hookham	Up to 25	0·350+
Chamberlain and Hookham	50	0·100+
Bat	House service	0·090+
O.K.	House service	Nil
B.T.H., type M.H.	Various	0·35 + to nil
Motor Watt-hour Meters.		
Aron A.C.	House service sizes	0·045+
A.C.T.	House service sizes	Nil
Bat	House service sizes	0·076+
Ferranti A.C.	House service sizes	0·038+
Electrical Company's ...	House service sizes	0·077+
Eclipse	House service sizes	0·104+
Scheeffer	House service sizes	0·025+
Stanley	House service sizes	0·079+
Thomson type R. H. ...	House service sizes	Nil
Thomson types T.S. and T.A. with copper potential resistances	Various sizes	Nil
Thomson types T.S. and T.A. with Eureka resistances	Various sizes	0·320+
Thomson type C.	House service sizes	As T. S. and T. A. types
Chamberlain and Hookham, unshunted C.C.	Up to 50 amperes	0·142+
Chamberlain and Hookham, shunted	50 amperes and upwards	0·050+
Aron C.C.	House service sizes	0·300+
Clock Meters.		
Aron, shunted	—	0·270—

per cent. of accuracy with a Kelvin balance and a standard clock beating seconds; that is the degree of accuracy that I believe can usually be obtained in work of this kind.

Dr. Russell.

Dr. A. RUSSELL: I have been very interested in both these papers. Mr. Melsom's is perhaps the more orthodox. His results seem to be in close agreement with my own experience. It was quite a common belief amongst many engineers a few years ago that if we were to put, for instance, a motor meter, like a Thomson-Houston meter, and a pendulum meter, like an Aron meter, on a tramway load there would be a difference between the readings. About a year ago I had to take up this subject, and I asked Mr. Silver to carry out a series of tests on fluctuating loads with actual tramway meters. We took the best types of meters on the market—both motor meters and pendulum meters—and we had them all placed in series and properly adjusted and calibrated. Mr. Silver then carried out a series of tests with both fluctuating and interrupted currents, and, as we expected, we found that the meters read the same. There was no error due to the fluctuation of the loads. We knew, however, that the meters read differently when they were put up on the switchboards, and therefore we investigated the probable cause of the error. We found that most of the meters are affected by stray magnetic fields; even the astatic meters were affected when the magnetic fields were not uniform. We found also that the pendulum meters were affected by want of uniformity in the magnetic field. We then tried the effect of vibration. We started a motor working on the bench where all these meters were arranged, and they were subjected to various degrees of vibration. In the motor meters we found that appreciable errors arose from this cause. The two reasons were sufficient to explain the discrepancy between the readings of the meters when mounted on the switchboard at the generating station. By putting my hand on the meters when they were mounted on this switchboard I found that when certain engines were working it was possible to feel that the meters were subjected to very appreciable vibration. With a little compass it was also shown that the magnetic field was large. As a matter of fact the final method adopted for metering the current was more or less in the nature of a compromise. The producer wanted a motor meter; the consumer wanted a pendulum meter; so as accuracy was of the highest importance no less than six meters were put in series in the circuit, three being motor meters and three pendulum meters. These were all calibrated at Faraday House. Four of them were then put on the switchboard, and the readings ought to have been the same, as they were all in series. But we were not surprised to find that there were discrepancies in the registrations. The differences were not large, but they were much larger than could have resulted from errors in testing. The remaining two meters, one a pendulum and the other a Thomson-Houston, were then used as standards. They were erected in series with the others, but well away from the switchboard in a place where the vibration was negligible and where they could not be affected by stray fields. The readings of the two standard meters agree almost exactly with each other. They were then taken back to Faraday House and a re-test showed that they were accurate within close limits. The motor and

pendulum meters for heavy traction loads nowadays are admirably made and excellently adapted for their work. I think the question of metering tramway loads is fairly simple provided that proper precautions are taken. If the meters are put away from stray magnetic fields and are not subjected to vibration, the readings will agree amongst themselves, and very different types of meters will record the true load. I think, therefore, that the authors' statement that there are no standard meters which can be used for tests in position, is open to question. It is no good taking a meter off a switchboard and sending it to a testing institution and then putting it up again. The vibration and the stray magnetic fields have to be taken into consideration, so that, as Mr. Trotter suggested, to have a standard meter inserted in series, proper precautions of course being taken, is practically the best method of testing switchboard meters. Professor Robertson's paper is of particular interest to me. The mathematical theorems given in the Appendix are thoughtful, suggestive, and instructive. The notation the author adopts makes it rather difficult to follow them owing to the necessity of continually turning up the table of symbols. I agree with the formula he gives for the record of a meter when starting and stopping when it is subjected to a parabolic law of friction. The fractional error he finds to be— Dr Russell.

$$\frac{T_0}{b\,T_a}\log_\epsilon\frac{(1+b)^2}{1+2b}.$$

As Professor Robertson points out, this vanishes when b is zero, *i.e.*, when the fluid friction torque is negligibly small compared with the eddy-current torque. But when b is about 1·54, the fractional error attains a maximum value of 0·298 T_0/T_a, and when b is infinite it again vanishes. It appears, therefore, that it should also read correctly when the fluid friction torque is very great compared with the eddy-current torque. But this case cannot be deduced from the author's theorem as the assumptions are then unpractical. It would be interesting to know what justification the author has for the statement that "any wave can be built up of a series of rectangular waves."

Mr. A. J. CRIDGE: With reference to various points mentioned in Messrs. Melsom and Eastland's paper, I should have thought it would have been found that the astatic windings now adopted in so many motor meters, and in our own oscillating meters, would have obviated any trouble which is experienced with stray fields. It is frequently necessary to guarantee meters against being affected by stray fields. The A.E.G. has submitted some to tests in their own laboratories, and have found them to be, so far as could be judged, satisfactory. Further, if the steel spindle causes any trouble, our oscillating meter has an aluminium spindle, which should get over that difficulty. On page 480 the authors refer to the possibility of using meters in parallel. I do not think that is a very practical suggestion, and I have never seen it done. With reference to the 4,000 ampere-meter mentioned, which was tested cold and then tested hot, was it tested again after it had Mr. Cridge.

cooled down, and if so were the results the same or not? I am sorry to hear that Professor Robertson is not able to be present to-night to read his paper, because there are a number of things I should like to have said in his presence. I have myself inspected the apparatus on which his tests were made, and I have no complaint to make about the way in which they were carried out, or about the apparatus itself. But I do say that the tests have very little practical value, and do not represent anything we are likely to meet with in practice. When we have as in these experiments a continuous current which is interrupted so many times in a second that it actually has a root-mean-square value we cannot expect a continuous-current meter to operate very accurately on it. Something of the B.T.H. type with a rotating armature which deals with the pressure must be used. So that when Professor Robertson says that he has subjected these meters to certain tests, the results of which verify his theories, I might equally say I have put a continuous-current field on an alternating-current meter, with alternating current flowing through the main coils, and that the meter did not turn round, and that that fact verified the theory I had worked out about it. Nobody supposes that a meter would work under such conditions. Mr. Trotter referred to the question of the Board of Trade approval. Both of the meters which Professor Robertson had are now of approved types, though one of them, the ampere-hour meter, was not at that time approved. They must therefore be taken to be reasonably useful meters. They do not appear so, I think, from Professor Robertson's curves and figures. With regard to larger sizes of meters, we propose applying to the Board of Trade for approval of our big types very shortly. Professor Robertson refers on page 506 of his paper to the fact that the oscillation of the watt-hour meter appears to introduce troubles of its own. That does not seem to be verified by the investigations of Orlich and Messrs. G. Schulze or Messrs. Melsom and Eastland, and I am myself rather at a loss to know what those troubles were. I notice in Messrs. Melsom and Eastland's paper that they had to borrow one of the A.E.G. meters from the South Metropolitan Tramways Company. I was not connected with the A.E.G. at the time, but if he would like to go further into the matter I can offer him, or anybody else who wishes to make any tests of practical value, the use of as many meters, of any size whatever, as they think fit to ask for.

Mr. Cridge.

Mr. Rennie.

Mr. J. RENNIE: I think we shall all agree that the conclusion at which the papers now before us this evening have both arrived regarding the metering of variable loads has settled that question once for all, and I regret very much that Professor Robertson is not present so that he might hear it from the meeting. I am afraid I cannot quite agree with all that Dr. Russell has said with regard to Professor Robertson's paper. The experiments were of a painstaking nature and very carefully done, but as a piece of laboratory work there must be a word of warning to our younger men against accepting some of the conclusions at which he appears to have arrived, and with regard to some of the apparatus which he used. Take, for instance, his electrolytic

cell. If we look at Fig. 7 we find that the plates are hung or supported by screw bolts and nuts. That is a very unsafe method, because the plates have to be removed from the cell, very carefully dealt with, and weighed. There is no need for such an arrangement, because it is quite a commonplace piece of mechanism to support these plates so that they are simply slipped into position. While speaking of that part of the appliance attention might be directed to the similar apparatus used by Messrs. Melsom and Eastland. Their voltameter was admirably suited to its purpose, and I would specially draw attention to the clever arrangement adopted for securing an adherent and well-distributed deposit. I think Mr. Melsom told me—I do not know whether it is mentioned in the paper—that the result of that arrangement was to make it not so absolutely necessary that the handling and the weighing should be done instantly, that it might even be left for as much as a day. In dealing with the meters it might have been well if Professor Robertson had adopted the methods used by Messrs. Melsom and Eastland. Their comparisons are made between A, B, C, D, and the rest of them, but we cannot tell whether A is an Aron or B a B.T.H. I think that is very wise, because after all the curves that are shown in both of these papers are curves taken under special conditions, and probably in the case of some of Professor Robertson's they were taken to accentuate peculiarities. Mr. Rennie.

We have been talking a good deal at the Institution lately about publicity. Just think what would happen if some consumer set his eyes on that very extraordinary curve, Fig. 13, in Professor Robertson's paper as resulting from certain tests made on an Aron meter. The consumer does not know much about electricity; he knows he has an Aron meter in his house, and here is a curve showing that at a certain time and for the conditions under which it was then working the error is infinity, and it is against him. For these reasons I think we should keep this question of publicity in our minds. If we wish to form opinions as to what meters are capable of doing, I wonder why the manufacturers of meters do not adopt a suggestion which they know they can carry out if they choose. They have only to ask. In getting approval for meters there is a specification furnished, and there are drawings, and also curves showing the characteristics of the meter. One of those curves is the accuracy curve. There are many others which it might be equally interesting to furnish. But if those curves were published showing what a manufacturer was prepared to guarantee under the terms of the approval which he has obtained from the Board of Trade, it would give a very different idea indeed of what was possible. I do not say that is always obtained, but still it is possible, and if a maker guarantees he can do that at any time, he can be made to do it. I speak with some hesitation as to the mathematical appendix attached to Professor Robertson's paper. It may be all right—I am prepared to take Dr. Russell's word for that—but we must remember that the basis of this mathematical theory is the three statements which Professor Robertson makes at the beginning of his paper.

Mr. Rennie. He says his solid friction is constant; his eddy friction follows a linear law, and his fluid friction follows a square law. To meter manufacturers I need not say that those conditions have absolutely no relation whatever to what takes place in an actual meter. And so I say that although Professor Robertson warns us that sometimes discrepancies have arisen, I think it is necessary to point out that probably the discrepancies are the whole story. I leave the mathematicians to examine that. What would happen if instead of having fluid friction varying as the square law it were found that it varies as the linear law or as to no fixed law? How that would alter the mathematical investigation!

With respect to the general conclusions set out on pages 508 and 509, where these are based upon experimental work given in the paper, I scarcely think that the author justifies his position with regard to Nos. 1 and 2. No. 5, where he speaks of simplicity, I cordially agree with, and so I think will most people who have to deal with meters. I agree with No. 6 as well, but I think his opinions as given in the remaining paragraphs are not sound; at any rate, I urge that they do not agree with practical politics in relation to the meter question at the present day.

I now come to Messrs. Melsom and Eastland's paper. In the types of meter that are dealt with there are two that rather interested me. One of them I had heard of, and I had a specimen of it in my hands a good many years ago now; it is Mr. Evershed's meter. We had that meter tested and found it very good—too good for common use. He tells me now, however, that his meter is better, and good for common use now. Apparently from Mr. Melsom's experiments that statement is perfectly true, and I am waiting with the very greatest interest to see it hurled at us with a demand for approval. The Everett-Edgcumbe meter I have never heard of. Meters are really handy travellers. We investigated this question very carefully a good many years ago, and exhausted our ingenuity in inventing difficult journeys. For one journey we sent the meter to Ireland, hoping that it would get very severely handled in the crossing of the Channel and in the transhipment from one place to another. But the meter came back with scarcely a change in it, so when we found that all this trouble of packing, and unpacking, and testing, and so on to ascertain the possibility of damage through carriage was quite futile we gave it up. I am glad to find that even now, as I quite expected, the makers have not gone back in any way on what they can do, and a meter can still travel better than many of us. The most interesting part of the paper, however, is the part from page 477 to the end. I have always felt that the authorities of electricity stations had not a proper appreciation of the meter question, and did not apply to the purchase, installation, and management of meters the amount of skill and care which their importance demanded. There is little doubt—we have seen it to-night—that the great majority of the troubles that have arisen through disputes about meter records were due, not to faults in the instruments them-

Mr. Rennie.

selves, but to faults in their initial purchase, in their installation, and in their daily use. I say "purchase" because we frequently find that meters of quite an ordinary type are suddenly promoted to become special meters. They are sent to the Electrical Standards Laboratory for the purpose of getting their constant to the last decimal place. The meters were never built for that purpose; they were of quite ordinary manufacture, and as Mr. Trotter has indicated, from the character of the case in which they came to us and the general appearance of the meter itself it simply looked as if it had been picked up from the scrap-heap. That, I say, is not fair. It is a matter of common knowledge that an electricity meter is put into any odd corner, without respect to the surroundings, magnetic or thermal; and it is no uncommon thing to find meters that have been used under these circumstances sent again for test, with the demand that the test shall be given to perhaps 1 per cent. That might be quite a reasonable figure, but it is usually 0·1 they ask for, until we put our backs up and say we will not have it. I sometimes wonder if it would not help matters a bit if the meter makers could induce the meter purchasers to spend a little more money so that the instruments themselves might be made handsomer. One finds meters—they have been through my hands—that were built, as the manufacturers say, for switchboard use; they are very pretty things indeed when built with an electroplate case and plate-glass sides, and the inside rather well finished and good-looking. That is a sort of thing that demands treatment that a meter not similarly clothed would not get; just as in dealing with an instrument of any kind, even a watch.

Some years ago Lord Kelvin delivered a lecture on the "Six Gateways of Knowledge"—I think I am quoting the title correctly—and part of his lecture was intended to justify the addition of the sixth. He suggested—he could not at the time make it more than a suggestion—that there should be a seventh. You can guess what that was—an electrical sense. But he went further and indicated a possible eighth—an electromagnetic sense. It seems to me quite possible that if an electrical engineer would devote his mind so to develop his electrical consciousness he would in time come to be more alive to the things that were likely to injure his affairs electrically or magnetically. His eye would be more accustomed to look for circuits that might carry currents that might disturb his meter, and he would not be found placing an ammeter on the frame of a running dynamo, neither would he be found fixing a meter on an iron railing within a few feet of a 200-k.w. generator. That I have seen in London. These things, I think, might be improved. I would strongly urge that the last pages of this paper from the National Physical Laboratory be carefully studied by those who deal with meters and with measurement. We may then hope for such an improvement in the electrical and the magnetic consciousness that "meter matters" will go very much better in the future than they have done in the past.

Mr. Smith. Mr. ROGER T. SMITH: All those who live—if I may use the expression—by the results of meter readings on variable loads, that is to say, authorities and companies who supply tramways and electric railways; the electric departments of railways who supply other departments; or electric railways that supply other electric railways—all those people are very much indebted to the authors of these two papers, since, as Mr. Trotter has put it, their experiments have decided once for all that a large number of meters are correct on variable loads if they are properly made and properly installed. Both Mr. Trotter and Dr. Russell have taken exception to the last paragraph of page 485 of Messrs. Melsom and Eastland's paper, in which they suggest that the use of a calibrating meter, which can be removed for test, is not satisfactory. I am glad to be in such good company in trying to prove by a practical illustration that I think the use of a calibrating meter is good practice. This contention holds only in cases in which the value of the energy passing through a meter in a year may amount to something of the order of £20,000, so that an error of 1 per cent. would mean something from £150 to £250 per annum. Under those circumstances I think that if there are installed meters of the very best manufacture that are obtainable—worth mounting, as Mr. Rennie has said, in glass cases with gilt frames—and three of them are used, very fairly accurate average results can be obtained and maintained. The diagram given in Fig. A shows results from three meters in series used on the Great Western Railway traction supply. Two of the meters which are installed permanently are partial fluid friction meters. The readings of one are marked R (right hand), and of the other L (left hand). A third meter of quite a different type, with solid friction instead of fluid friction, in which the whole current passes through the meter, is used as a calibrating meter in series with the other two. Its readings are shown in the diagram by dotted lines. The curves show tests made when all the meters were new, one taken over sixteen days at one sub-station, and another over six days at another sub-station. The little circles show the amount of the percentage difference between the three. It will be seen from the longer set of curves that over sixteen days the greatest difference between any meter compared with any other amounted to rather less than 2 per cent. in one sub-station, and in the other sub-station the error is so small that I think it does not show at all. That percentage difference remained perfectly satisfactory as long as the meters were new, but our experience has been that meters in which part of the friction is fluid have a tendency to run slow, due to causes which I will not attempt to specify. Our method of procedure is as follows. The B.T.H. meter is sent from time to time to the National Physical Laboratory for calibration. I have given the latest test curve of that meter on the top left-hand corner of the diagram; it is the curve that has already been shown on one of the slides illustrating Messrs. Melsom and Eastland's paper. It will be seen that after being calibrated cold it has a negative error. At a 2,000-ampere load, which is half the maximum load, it is very nearly right after that half load has

been going through the meter a couple of hours, and there is good reason to believe from repeated calibrations at Teddington that that meter is very accurate when working at the average sub-station load. Each of the sub-stations has a similar third meter, which can be readily removed from time to time for calibration at Teddington. The other Mr. Smith.

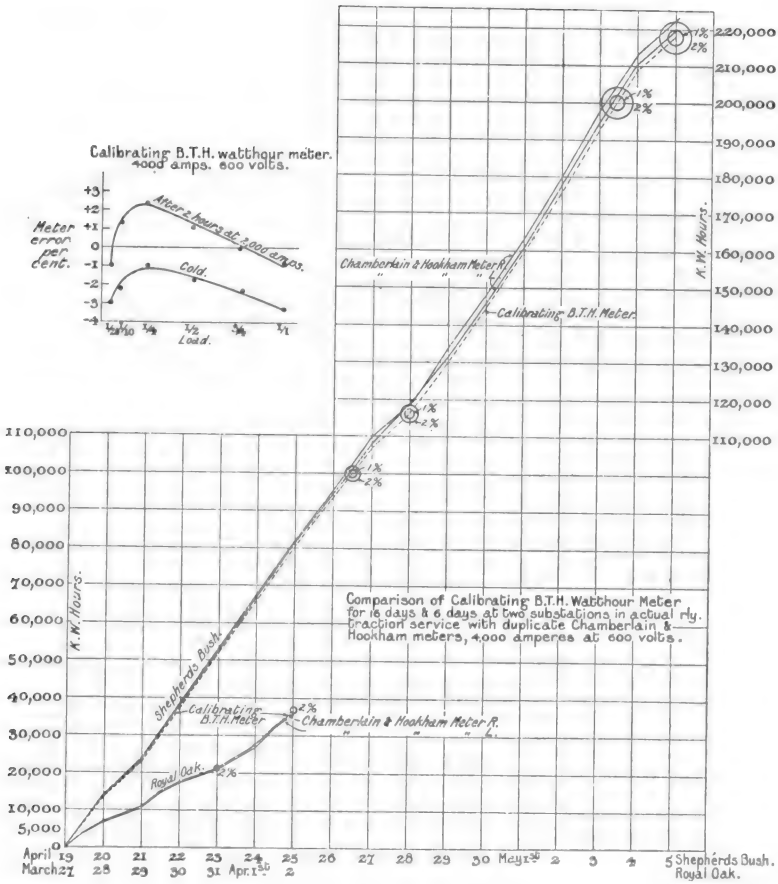


FIG. A.

meters are only removed whenever they want cleaning and recalibrating, which is done periodically. In general, as soon as any one meter differs from any other meter by 2½ per cent. the gear-wheels are changed without removing it from the sub-station, and as a result we generally get two meters reading on either side of the calibrating meter, so that we get average results agreeing with the calibrating meter within about 1 per cent. I may say that the position of these meters is as far away

Mr. Smith. from the switchboard as it can be, and that all the connections to them are permanent. We have made tests for ourselves of stray field effect with the shunt fields on only, and can get no motion, not only of the dial but also of the discs. I therefore differ from the conclusions in the last paragraph of Messrs. Melsom and Eastland's paper, and would ask if there is any other way by which satisfactory readings of these enormous quantities representing thousands of pounds of money can be obtained other than by using calibrating meters of this sort, removed from time to time for test by some such body as the National Physical Laboratory or the Board of Trade.

Mr. Young. Mr. A. P. YOUNG (*communicated*): Meter manufacturers throughout the country will welcome both papers for dealing so fully with the vexed and recurrent question of the accuracy of watt-hour and ampere-hour meters under variable load conditions. This particular aspect of the general problem of metering electrical energy must now be considered as settled, and the authoritative statements made in both papers (supported in each case by very careful experiments) should serve to dispel any lingering doubts that may still exist in the minds of central station engineers and others as to the accuracy of meters of the motor type when used to measure rapidly fluctuating loads. This problem has, however, not been overlooked by meter manufacturers, and we (I speak for the B.T.H. Company, Ltd., in particular) have long since been satisfied that all meters supplied by us (which are of the motor type) give accurate results on variable loads, and that the accuracy of the record made is for all practical purposes quite independent of whether the load is steady or fluctuating. The theory on the subject, with which we have been familiar ever since we commenced the manufacture of electricity meters, is quite simple and sound, and shows very clearly that the accuracy of a motor-meter having eddy-current damping and no uncompensated friction is quite independent of whether the load is steady or fluctuating. The practical side of the problem has, nevertheless, not been overlooked, and the General Electric Company of the U.S.A. some sixteen years ago carried out tests on the well-known Thomson watt-hour motor meter, which proved that the theoretical conclusions are justified in actual practice. It is true the tests were not carried out on such an elaborate scale as those referred to in the two papers, but they served their purpose. Actually three exactly similar meters were taken, two of these being connected in parallel with the third in series. A steady current was passed through the combination, and by means of a special form of switch the circuits of the first two meters were alternately broken and made. That is, whilst the load on the third meter remained steady, that on either of the first two meters was alternately zero, half load, and full load, the cycle being repeated periodically. The meters were run for ten hours under these conditions, and at the end of that time it was found that the sum of the readings of the first two meters differed by less than 1 per cent. from the reading of the third meter. These experiments made sixteen years ago are confirmed by the more

elaborate and refined tests made by Messrs. Melsom and Eastland, the results of which are given on pages 473 and 475 of their paper; also by those of Professor Robertson made on the B.T.H. type "C" and type "T.S." meters, the results of which are shown by the two top curves of Fig. 11 in his paper. If we examine the theory we shall find that any motor meter which has to measure the product of some quantity (A), and the time (t), will record correctly regardless of how (A) varies, provided that: (1) The driving torque is directly proportional to A; (2) the retarding torque is directly proportional to the angular velocity of the moving system, and there is no extraneous friction or damping not in conformity with this law. Mr. Young.

This is at once apparent if we write down the equation of motion governing such conditions:—

$$K . A = I . d\omega/dt + K_1 . \omega,$$

where I = moment of inertia of the moving system, ω = angular velocity of moving system, and K and K_1 = constants. Multiplying through by dt and integrating we get:—

$$K . \int_{T_1}^{T_2} A . dt = I \int_{T_1}^{T_2} d\omega + K_1 . \int_{T_1}^{T_2} \omega . dt,$$

i.e.—

$$K . \int_{T_1}^{T_2} A . dt = I (\omega_{T_2} - \omega_{T_1}) + K_1 (\theta_{T_2} - \theta_{T_1}).$$

If we assume that initially at time T_1 the moving element is at rest, and also at the final time T_2 it has again come to rest then:—

$$\omega_{T_2} = 0 \quad \text{and} \quad \omega_{T_1} = 0$$

$$\therefore \quad K . \int_{T_1}^{T_2} A . dt = K_1 (\theta_{T_2} - \theta_{T_1}).$$

The quantity on the left-hand side of this equation is that which has to be measured, whilst that on the right-hand side is proportional to the total angle moved through by the moving system, that is, to the number of revolutions made in the period from T_1 to T_2. This brings us to the question of ampere-hour motor meters of the mercury type wherein eddy-current damping is employed. The curves given for two well-known makes of meter of this pattern in Fig. 9 of Professor Robertson's paper, would seem to indicate that the errors on fluctuating loads are by no means negligible even on low frequencies, thus showing that the two fundamental conditions enumerated above are not fulfilled in the meters under consideration. As a matter of fact the extraneous damping produced by mercury friction is not a negligible factor, and in all three types of meter a compounding coil is introduced for the purposes of compensating for the mercury friction, more particularly

Mr. Young. on high loads where it becomes of increasing importance. Professor Robertson does not put forward any suggestion as to why the discrepancy is greater in the case of the mercury meters tested than it is in the case, for instance, of the B.T.H. meters, the curves for which are shown in Fig. 11. In this connection I would put forward the suggestion that the error results in most part from the compounding coil employed to counterbalance the effect of mercury friction, as a result most probably of some hysteresis effect in the magnet system; that is, the flux change necessary for true compensation does not occur when the current in the compounding coil is fluctuating rapidly, with the result that true compensation is not achieved, and the deleterious effect of mercury friction manifests itself by causing the meter to read considerably more than it should do. It is, therefore, very unfortunate that Professor Robertson did not carry out tests on the mercury meter manufactured by the B.T.H. Company, wherein there is no compounding device of any kind. By a special construction, a very strong concentrated permanent magnetic field is obtained which acts as the driving as well as the braking field, and as a result the speed of rotation corresponding to full load is kept very low. Now for very low surface speeds there is evidence to show that the mercury friction is for all practical purposes directly proportional to the velocity, and the mere fact that in the meter in question the natural characteristic between full load and very low loads is approximately a straight line, proves conclusively that the mercury friction (which is, of course, an almost negligible factor for such low surface speeds) does, nevertheless, obey the same law as that of the eddy-current damping. With the B.T.H. mercury meter therefore, we should expect that on fluctuating loads the characteristic is not appreciably affected, and I have little doubt that careful experiments would support this conclusion. As mercury type ampere-hour meters are being used more and more for tramcar service, the above conclusions would seem to show that meters in which compounding is employed are not so suitable for this class of service as that type in which the design has been so carried out that a compounding device is found quite unnecessary.

The sweeping statement made by Professor Robertson in respect of mercury meters and given under "General Conclusions," paragraph 2, page 508, is therefore unwarranted, particularly as he tested the products of two manufacturers only, in one case the meter being a very old pattern. In view of what has already been said in respect of the law governing mercury friction for very low surface speeds, the assumption made in Professor Robertson's mathematical appendix and given on page 509 to the effect that the law is parabolic is open to strong suspicion. Beyond a certain critical speed the law is most probably in accordance with the assumption made by Professor Robertson, but the whole question of fluid friction is rather complicated, the law apparently changing as the speed increases. We have, therefore, to be very careful in making any assumption with regard to the question. Strong exception must be taken to the second paragraph,

page 508, of Professor Robertson's paper, in which reference is made to the B.T.H. Thomson watt-hour meter. This is one of the many unwarranted sweeping statements made in the paper, and in the present instance the statement made as to the accuracy of this type of meter after it has been in operation for some time is quite inaccurate, and certainly not supported by users throughout the country. Neither is it confirmed by the careful tests made at the National Physical Laboratory and described in Messrs. Melsom and Eastland's paper under "Constancy of Calibration." These tests extended over a period of eight months, during which time the meters were twice despatched on railway journeys, and they show that there was no such change in the accuracy. Reverting to Messrs. Melsom and Eastland's paper, that part dealing with the "Effect of stray fields" is exceedingly interesting and of great practical importance. It is unfortunate that tests were not made on any astatic type-meters. Above 500 amperes all direct-current watt-hour meters manufactured by the B.T.H. Company are of the astatic type, and they are therefore unaffected by uniformly distributed stray magnetic fields in the region of the two armature coils. As the armatures are very close together, the result is that any stray magnetic field resulting from adjoining conductors has no appreciable effect on the accuracy of the meter. Meters for currents less than 500 amperes are not astatic, as it is safe to assume that the currents carried by conductors placed in close proximity to such meters will be correspondingly small, so that the stray field effect is almost negligible. Under "testing" it is pointed out that the possible error in calibrating a direct-current watt-hour meter is plus or minus 1 per cent. It is interesting to have an authoritative statement with regard to this point, and the fact that such a statement has been made by those having the elaborate resources of the National Physical Laboratory at their disposal, should be brought to the attention of all those interested in the meter problem. It is simply for the lack of appreciation of a simple fact of this kind that such absurd guarantees are from time to time asked for. Mr. Young.

Mr. H. E. Trent (*communicated*): With regard to the statement by Messrs. Melsom and Eastland at the bottom of page 473 and top of page 474 it is not clear what is the exact meaning of this, nor does it seem to be in agreement with the curves 5 to 15. Whilst the altering of the ciphers for the further tests mentioned in the middle of page 475 prevents misleading conclusions, it does also detract from the ultimate value of the paper, as most manufacturers of meters would welcome careful criticism. The authors state on page 476 "there was no appreciable change in the calibration of any of the meters as a result of the travelling." If this is so, to what cause do the authors put down the alterations in the calibration they show in curve 5? The effect of stray fields, I take it, applies only to one meter. There is no doubt that cast-iron cases do affect the accuracy of meters if such cases become magnetised—and I have found instances when it is necessary to anneal cases in course of manufacture after all Mr. Trent.

Mr. Trent. machining has been completed—the stoving whilst enamelling often has the desired effect of annealing the case. Whilst in agreement with the statement that care in erecting meters may obviate any effect of stray fields, this is often difficult to predetermine. In the case of meters of the Thomson motor type the starting coil can be adjusted *in situ* to correct meters at low loads. *Levelling*—Here again it would have been useful to have known the type of meter affected by being 3 degrees out of level. Most manufacturers seal the cases of their meters and are relieved of their guarantee if the cases are removed. Would it be necessary to fix spirit-level or plumb-bob on all meters? If not, will the authors say on which type. However much the parts of meters are standardised, the changing of coils, clockworks, and magnets is not to be recommended. It is found more satisfactory, and cheaper, to replace the meter when a larger capacity meter is required. I have found, as the authors point out, that shunted meters require very special connecting up in order to avoid inaccuracies. An error of 30 per cent. may easily be realised. The authors have made it very clear that the test *in situ* is unreliable, or rather leaves ample room for inaccuracies owing to the inherent inaccuracy of standard intergrating meters, but if such stray fields are inherent to the lay-out of the plant, of what use is it to take a meter away to adjust within 0·5 to 1 per cent? It seems imperative that the meter should be tested *in situ* whenever necessary. It would be of interest if Dr. Robertson would explain how he arranged his test *in situ* mentioned on page 490 of his paper in view of the statements made by Messrs. Melsom and Eastland.

Mr. Moore. Mr. A. E. MOORE (*communicated*): There is one point touched upon in Messrs. Melsom and Eastland's paper which is of considerable interest to me at the present time. On page 477 the authors refer to the magnetisation of the iron shield used to protect the brake magnets affecting the accuracy of the meter, their later conclusions being that it is the spindle which becomes magnetised. I recently had to test a B.T.H. 600-volt, 3,000-ampere direct-current meter which had been used in an important test. The brake magnets were entirely enclosed in a thick iron box and the main current circuit consisted practically of a straight copper bar. With this meter it was found that the registration differed by some 4 to 5 per cent., depending upon the direction of the currents through the coils, the rotor always, of course, going forwards. The effect did not appear to be due to stray magnetic fields external to the meter itself, since a considerable rearrangement of the main connecting leads had no measurable effect on the accuracy. Moreover, it was not the low-load accuracy only which was affected, a difference of 5 per cent. being obtained with a load current of 2,000 amperes. I hope shortly to have the meter again for the further investigation of the cause of this result. It may, or may not, be due to the magnet shield. I have experimented with 10-ampere, 200-volt meters of this type without magnet shields, but have failed to obtain any measurable change in the accuracy by the reversal of the current. I should be glad to know whether the authors

have made any tests of this sort on the meters provided with magnet shields, and if so what results they obtained. With regard to the effects of external stray magnetic fields, those usually met with in a large direct-current generating station are far in excess of that produced by a 1,000-ampere busbar placed as suggested, and in addition it must be remembered that in proximity to the busbars—carrying several thousands of amperes—there is the iron-work of the switchboard, and this I have often found to be very powerfully magnetised. In places where these powerful stray magnetic fields obtain, it is probably more expedient to install meters which are practically unaffected by stray fields, than to endeavour to place the meters out of the field or to resort to magnetic screening. On page 479 the authors refer to temperature coefficients and state that this coefficient did not exceed $\pm$ 0·1 per cent. per 1° C. in the meters tested by them. This is smaller than usually met with in meters of the Thomson type, and is presumably effected by making the pressure circuits practically of copper. This would account for the nature of the curves shown on page 478. If the pressure circuits had a negligible temperature coefficient the meters would probably register faster at the high loads as well as the low, with increased applied voltages, since the meter would be over-compensated for friction. It would appear that the increased voltage causes a rise in the temperature, and consequently in the resistance of the pressure circuit. Meters of the induction type will register faster at light loads and slower at heavy loads with increased voltage on account of the braking action of the increased volt flux. Mr. Moore.

I am afraid I cannot entirely endorse the authors' preference for what they term a "chronograph" as distinct from a stop-watch. I am inclined to believe that the chronograph is the less reliable. I have not, however, had experience with expensive instruments of either type. I have often studied the starting of the centre-seconds hand of a chronograph, and sometimes it appears to hesitate before starting, whilst at others it immediately jumps forwards $\frac{1}{5}$ second or more, and this presumably depends on the instant the wheels are thrown into mesh. Another curious effect which I observed in a particular chronograph was that if the centre-seconds was checked by means of a seconds' pendulum it invariably gained $\frac{2}{5}$ to $\frac{3}{5}$ of a second in the first 20 seconds, but came out quite correct when the full minute was completed. I think it was probably due to the centre-seconds pivot and wheel being slightly eccentric with respect to each other. The watch I use for meter testing I had specially made. It is on the principle of an ordinary stop-watch without an hour-hand. The seconds' dial is about 3 in. in diameter and divided into fifths of a second, and a small dial is provided graduated to 60 minutes. The wheels driving both hands are in the main train, so that there is no back-lash. With the springing minute-hand usually provided in chronographs, I have often found that if the watch is stopped just when the minute-hand is being moved, the seconds-hand may be moved backwards or forwards about $\frac{1}{2}$ a second due to the spring on the minute-hand. A fly-back

Mr. Moore. centre seconds is undoubtedly more convenient to use, but I incline to the stop-watch for reliability.

Professor Robertson refers in his paper (page 508) to the straining of the coils of a Thomson meter due to heavy overloads and short circuits. The abnormal mechanical forces exerted on the coils when a short circuit takes place do not appear to be widely realised. I have seen a meter of this type taken off circuit with the main coils pulled up together on to the armature, the supports of the coils being completely twisted out of shape. In another meter of the same type which was brought to my notice the meter had been connected up wrongly, so that the starting coil, instead of aiding the main field, opposed it. The result of a short circuit was to force the starting coil right out of the main coil. I think, therefore, that there is very substantial evidence in support of Professor Robertson's view that this effect is partly responsible for the alteration in the constants of the meters when on circuit. I have, however, very little faith in the effectiveness of magnetic screens in the presence of such powerful fields as obtain in a meter due to a short circuit.

Mr. McInnes. Mr. C. F. McInnes (*communicated*): I believe the best result can only be obtained by tests in position. Mr. Rennie in his remarks suggests that where there has been trouble the engineers are primarily at fault in that they do not give the meters sufficient care (because the containing case is not sufficiently elaborate), but the fact remains, and I think all engineers who have had much to do with traction meters will agree that however careful one may be, in position the meters may or may not, and frequently do not, give the same results as in a laboratory. It would appear as if the meter intuitively knew that in the calm cool of the laboratory it was on its merits and must justify its existence, whereas in the hurry and bustle of station life it adopted a somewhat different attitude. I should like to ask Mr. Melsom if he made any tests as to the effect of vibration on the meters. I believe this to be an important point. Further, where different types of meters, say pendulum and motor, are connected in series, small influences might affect one meter in a positive and the other in a negative direction, and though the individual error might be admissible the combined one is not. Now to my main point; I agree a standard check meter is liable to error, but is it not possible for the National Physical Laboratory to construct a portable copper voltameter and make arrangements to take tests *in situ?* I am sure there are many station and tramway engineers to whom such tests would be invaluable.

Mr. Ratcliff. Mr. H. A. Ratcliff (*communicated*): I am rather surprised to note the use of the word "power" on the last line of paragraph 2 in Messrs. Melsom and Eastland's paper; "energy" was no doubt the word intended. It is unfortunate that meters of such a small size as 200 amperes were selected for test, as this is surely an unusually small size in central station work, and, moreover, many of the troubles incidental to the use of meters only become appreciably apparent in the larger

sizes, say 1,000 amperes and above. The outstanding feature in both papers is the fact that all the meters have been tested as ampere-hour meters, or coulomb meters, although in one case all the meters tested were actually of the watt-hour type. In can hardly be assumed that the voltage is constant, even in the best regulated traction generating stations, under certain conditions it may be very variable, and it is for that reason that appreciable errors may arise in the registrations of certain types of watt-hour meters when running on variable loads; and as the authors are continuing their observations, it might be of interest if they were to investigate the nature and extent of such possible sources of error. In the series of curves showing the constancy of calibration of the various meters over a range of thirty-six weeks, there is in every case a most marked irregularity in the results on full and quarter loads during the interval between the fifth and ninth weeks, but curiously there is no corresponding variation in the $\frac{1}{10}$-load results. I should like to have the authors' explanation of these variations. Similar curves to the one obtained by Professor Robertson, showing the effect of a critical frequency of load fluctuation upon the accuracy of "Aron" clock meters, can also be obtained with a steady load, as it is frequently possible to find one particular load at which the oscillations of the pendulums are of very nearly the same frequency, the result being that mechanical resonance occurs, tending to keep the pendulums in step, and thus producing considerable errors in the registrations. This effect can be overcome by fixing a fairly heavy flywheel on the counter transmission gear. The results of fixing meters out of level are interesting, as it is not at all unusual to find meters so fixed. In this respect clock meters possess the advantage that if appreciably out of level, their registrations become so erratic that the cause of the trouble is at once obvious, and may therefore be rectified. Mr. Ratcliff.

On page 480 of Messrs. Melsom and Eastland's paper, the authors refer to the substitution of meter shunts, and on page 482 reference is also made to the connections of shunted meters. Now, the question of shunted *versus* total current type meters is so important that the authors might well have enlarged upon the subject with advantage. I had occasion to go into this matter very thoroughly some years ago, and, as a result, decided that it was advisable to shunt all meters larger than 2,000 amperes' current-carrying capacity, and it is probable that in the future this limit may be even reduced to 1,000 amperes. The following are probably the chief advantages and disadvantages of shunted type meters: *Advantages*—(*a*) The meter may be fixed conveniently and easily without fear of mechanical strain when making the connections (this is a very important point, as it is almost impossible to make the usual cable or strip connections to, say, a 5,000-ampere meter, without seriously straining the meter, or disturbing the level). (*b*) The shunt of the meter may be fixed in any convenient part of the circuit, and the cost of connection is therefore, as a rule, considerably reduced. (*c*) It is usually possible to fix the meter away from the influence of disturbing local magnetic fields.

Mr. Ratcliff.

(*d*) The meter may be removed for adjustment or cleaning, etc., without disturbing the main connections or interrupting the supply. (*e*) It is possible to test any size of meter, however large, with comparatively small currents. This may be done by carefully measuring the resistance of the shunt and testing the meter on a smaller shunt with the corresponding voltage drop. Extensive check tests have shown that this method is both legitimate and reliable in the case of clock meters. (*f*) Shunted meters are not affected by heat arising from bad contacts in the main circuits. (Errors due to thermal E.M.F.'s may arise, but can be guarded against.) (*g*) If it should be necessary to enlarge the current-carrying capacity of the meter, it is an easy matter to change the shunt and alter the dial gearing of the meter to correspond. *Disadvantages*—(*a*) Temperature errors may be considerable. In the case of shunted "Aron" meters, the error may amount to as much as 0·15 per cent. per ° F. (*b*) Great liability of error due to bad contacts. This is a very serious source of error, and in some cases it is very doubtful if it can be completely overcome. The best means of eliminating the error from this source are: (1) The shunt should be designed to work with the maximum permissible voltage drop, and, if possible, this should not be less than 0·2 volts, except in the case of very large shunts. (2) The actual meter current should be small, and preferably not more than 5 amperes. (3) Duplicate meters and shunts should be installed on all important circuits, as by this means bad contacts are usually indicated by a considerable difference between the readings of the meters. Incidentally it is bad practice to connect the two meters to one shunt. If the above points are observed, and the connections are clean and tight originally, there is very little error due to contact trouble, particularly if the contacts are examined occasionally. In the case of shunted watt-hour meters of the mercury motor type, the volt drop on the shunt is, as a rule, only about 0·1 volt, and the meter current is usually about 50 amperes. The risk of contact error is therefore very considerable, and my experience is that it is extremely difficult to ensure that the contact conditions when the meter is installed are the same as those obtaining in the test-room, and, in any case, it is only a matter of time before contact troubles develop. (*c*) Errors on fluctuating loads due to the fact that the meters are shunted. This is a source of error on which I should like some quantitative information, but so far as I am aware, it is a point which has not been considered by the various experimenters, who have merely tested watt-hour meters as coulomb meters. My view of the case may be wrong, and I am therefore open to correction, but it appears to me that under actual working conditions, there is (in a much less degree of course) a similarity between the conditions obtaining in a shunted watt-hour meter on a direct-current fluctuating load, and a meter on an alternating-current load having a power factor less than unity. If the voltage on the direct-current system is constant, then the conditions are practically the same as for an ampere-hour meter; but in practice the voltage is fluctuating between fairly wide limits, and such fluctuation may be considerably out of phase with the current fluctuations. It is therefore

Mr. Ratcliff.

obvious that a shunted watt-hour meter may read either high or low, depending on the phase difference between the main current and the voltage fluctuations, and the phase difference between the current in the meter coils and the current in the shunt. It is possible that in actual practice these errors are not excessive, and, moreover, are continually changing sign with consequent elimination, but I do not see how there can be any doubt as to their existence.

The connections to meters of the total current type require very careful arrangement in order to overcome errors due to the resulting stray magnetic fields. The authors' suggestion with regard to the running of these leads is sound, but at times difficult to follow out in practice. Probably the best arrangement, although one which it is rarely convenient to use, was the one adopted by Mr. Wordingham some fifteen years ago. He designed a special system of connections for the large direct-current watt-hour meters in the Manchester station. One lead consisted of a solid copper rod, and the other of a copper tube fitted over the rod, thus forming a concentric conductor free from external magnetic fields. By means of a screwed contact operated by a heavy hand-wheel, the outer and inner conductors could be quickly connected together, thus short-circuiting the meter in the event of it being necessary to remove it for any reason. With regard to the strength of stray fields, I think that in many cases their effect is very much greater than is generally imagined, and I have seen cases in which busbars carrying 10,000 amperes were only a few feet away from the meters. When testing some "Aron" shunted direct-current meters for the effect of stray fields, a laminated iron core surrounded by about 2,500 ampere-turns, was placed only 6 in. away from the meter coils, and the difference in the readings of two meters on which the action of the electromagnet was of opposite sign, was inappreciable. Three of these meters (6,000 ampere 500 volts) are now working within 1 per cent. of each other, although fixed immediately over cables and shunts carrying as much as 7,000 amperes, and this agreement is all the more remarkable in view of the facts that the temperature of the surrounding atmosphere varies over a range of at least 30° F., and that the meters were all calibrated on different dates by the indirect method. The method suggested for detecting the presence and action of local fields is correct so far as it goes, but it must not be overlooked that the stray fields frequently alter the strength of or distort the field of the meter's brake magnets, and this would not necessarily be indicated by the method of detection suggested.

Messrs. Melsom and Eastland state that the limit of accuracy of 0·5 per cent. in the testing of watt-hour meters only applies to the special case where all current and voltage measurements are made on the potentiometer. This does not agree with my experience, and a similar degree of accuracy can undoubtedly be obtained if carefully checked and calibrated deflection instruments are employed. The whole secret lies in the use of suitably calibrated instruments. All voltmeters should have suppressed zeros with good open scales over the working portions

Mr. Ratcliff.

of the range, whilst the ammeters should be calibrated in conjunction with a series of universal shunts, so graded that whatever the value of the test load, a good open scale reading may be obtained. This method has many other advantages, two of the principal ones being: (*a*) That a meter may be tested throughout its whole range on one instrument, and each load current may be read with an equal degree of accuracy; (*b*) the ammeter may be permanently connected by means of tightly clamped or soldered connections to the ends of the shunts, thus avoiding the use of flimsy and unreliable flexible connections and plug contacts, etc. The various ranges are then selected by means of a switch in the main circuit, and consequently any switch contact errors are entirely eliminated (see Fig. B). I can confirm from my own experience the necessity for leaving the pressure on the shunt circuits of watt-hour meters overnight before testing.

My experience with watches has been the reverse of the authors', and I find that, as a rule, stop-watches are more reliable than chronographs; but of course I am referring to test-room conditions, which are rather more severe than those obtaining in a laboratory, as a watch is in constant use, and may be stopped and started hundreds of times a day, week in week out. I am in full agreement with the authors regarding the value of tests made in position, and can only suggest check tests with a standard "Aron" meter—a method which we have found reasonably reliable in practice. Experience has shown that the calibration of station meters of the motor type varies considerably during every hour of the day, according to the extent and direction of the local stray fields.

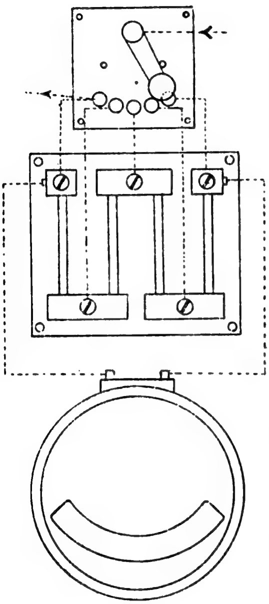


Fig. B.

Professor Robertson suggests that movements of the main current coils may contribute to the observed inaccuracies of motor meters, but the same effects are observed when the coils consist of a single turn formed of a solid copper casting bolted to a slate or marble base. Very little has been said with regard to the effect of short circuits and momentary overloads, although in practice these are the most disturbing influences encountered, and frequently after the calibration of meters to a very considerable extent.

Professor Robertson.

Professor David Robertson (*communicated*): There is one point about the action of the copper voltameter on variable loads upon which I had some doubts while carrying out my own experiments, and upon which the authors may be able to throw some light. Are we justified in assuming that the electrochemical equivalent is the

Professor Robertson.

same with the same mean current whether the copper is deposited at a uniform rate, as in the steady load tests, or in spurts, as in the variable load ones? In other words, is the rate of solution of copper deposited at a high rate the same as that of copper deposited at a slow rate? The differences in the nature of the surface in the two cases would lead us to suppose that some difference in solubility is at least possible. My attention was specially directed to this on one occasion when an accidental shut-down occurred during the time that the apparatus was left unattended. The cathodes were then found to be badly oxydised. The necessity for renewal of the acid mentioned by Messrs. Melsom and Eastland also points to an appreciable solvent action of the electrolyte which would make the effective electrochemical equivalent smaller than that applicable to a steady load equal to the maximum of the intermittent load. Probably the authors will be able to form some estimate of the importance, or otherwise, of this solution by comparing the ratio of the acid added in their experiments to the copper deposited. In my own tests the results varied so much from one type of meter to another that I thought I might safely neglect the effect now under discussion; any peculiar behaviour of the voltameter could not affect the general character of the results, but might make some of the meters appear worse and others better than they really are. On the whole, the National Physical Laboratory experiments and my own confirm one another so far as they cover the same ground. I understand that the former only went up to a load frequency of thirty interruptions per minute, at which my experiments did not indicate any very large variable load peculiarities for those types of meters which are common to both sets of tests. It should be noted that the Hookham meters were of different types. The ones I used were the well-known ampere-hour meters which had already been in service; that tested at the National Physical Laboratory is their more recent type of watt-hour meter. The interesting statement is made in a footnote on page 477, that the irregularities produced by momentary excessive loads was traced in one case to the magnetism of the spindle. Has this been definitely proved? It is difficult to see how it could produce any ncrease of speed (the usual result of overload) and any decrease which might be due to it could not be expected to be large. Since the spindle forms part of the rotor of the meter it could only produce a driving torque with continuous-current meters if its magnetism got reversed every half revolution. It might cause a retarding torque by inducing eddy currents in adjacent fixed metal parts, but we should expect this to be very small owing to approximate symmetry of the magnetism. Still, it is wonderful what large effects can be produced by apparently symmetrical magnetised bodies. Some time ago I had occasion to overhaul a number of pivoted magnetometers. In every one of them the needle could be deflected by turning the box. As I did not then believe that any appreciable directive force could be exerted on the needle by any slight want of symmetry which the pivots

Professor Robertson.

might have (they looked all right), I searched for paramagnetic particles in the brass, woodwork, and even the glass, but found none. So I was forced to the conclusion that the pivot must be to blame, and proved that this was so by strongly magnetising the biggest one, when the needle could be turned nearly right round by simply rotating the box. The fault was cured by using brass stems with only a tiny tip of steel. It does not, however, seem reasonable to explain any cumulative effect of excessive loads by acquired magnetism of the iron parts of the meter. The first heavy load may be expected to give these parts as much magnetism as they can retain, unless they happen to bring it just to the steep part of the curve, when there would be some cumulative effect for a time only. If this were the cause we should expect the meter to change erratically after a heavy overload, and then to recover slightly, or remain about the same until a greater one occurred; even if there were some cumulative effect, a limit would soon be reached when the material is as strongly magnetised as it can be. I have suggested that the mechanical strain of the meter coils by heavy short circuits may account for part of the gradual increase of speed often noted.

Mr. Clark.

Mr. E. V. CLARK (*communicated*): An instance of serious discrepancy between meters on tramway loading may be of interest to members, though I am unable to advance any complete explanation. A 600-volt direct-current supply was being given by a lighting company to a tramway undertaking, and to measure this there were installed two meters in series: one a 1,500-ampere Thomson motor-meter, and the other a 5,000-ampere oscillating-armature A.E.G. meter; the maximum rate of supply being initially 1,200 amperes. These meters were carefully checked *in situ* against ammeter and voltmeter every six weeks or so, at a steady load of about 600 amperes, obtained while charging the tramway battery, and adjusted to read alike; but their daily readings invariably showed that the motor meter ran the faster by some 2 per cent. or so. In the early stages of the supply, when the average all-day load was small, the motor meter was accepted as correct, and the difference in reading attributed to possible inaccuracy of the oscillating meter at very low loads, the average load at this time being but 10 or 12 per cent. of this meter's rated capacity. But as the load increased, and more particularly when the maximum current to be taken was raised to 1,500 amperes, the discrepancy between the meters grew more marked; while attempts to check their accuracy on a tramway load kept constant with aid of an automatic battery booster within about 10 per cent. above and below normal, by the method of taking ammeter and voltmeter readings every 5 seconds during the test, showed invariably that the oscillating meter was the more accurate. Finally, after a comparison of hourly readings of the two meters with the charts of the recording ammeters of both tramway and supply authority had again shown the oscillating meter to be the more correct, and when it had been observed that according to the motor meter the average load for an hour at a time was appreciably above the limiting rate that the

supply authority had declared the maximum at which they could possibly supply, it was decided that the readings of the motor meter were unreliable, and the oscillating meter was thereafter accepted as standard. It would undoubtedly be rash to state that the inaccuracy of the motor meter was entirely due to the variable load; but nevertheless it was the accuracy of this meter shown by a steady load test while battery charging, immediately following a very unsatisfactory result of a test under running conditions, coupled with the agreement of the two meters on steady load and disagreement under tramway load, that caused a very careful study of the two meters to be made; and at first sight one must therefore suggest variability of load as the most probable culprit. Still stray fields may be the explanation, both meters being erected on a temporary switchboard some 10 ft. from the nearer of two 750-k.w. dynamo sets, of which one was used for supplying the tramways, and the one not so in use being available to assist the lighting load by means of change-over switches. But it is not evident why such stray field effects should be enhanced by variable load; for in every case the meters were tested *in situ* without any change in the leads. Again, the discrepancy between the meters increased markedly as the daily output rose, and from about 2 per cent. at first it rose to 5 or 6 per cent. in a few months, with increase of some 50 per cent. in units supplied, despite occasional tests on steady load when the accuracy of each meter appeared satisfactory. Finally, a few days after a further increase of some 25 per cent. in the daily output, the discrepancy increased markedly until it exceeded 10 per cent. on some days—possibly due to some alteration in the motor meter requiring adjustment, for no further steady load tests were made on this. Naturally, increased loading and more cars running means a smaller percentage variation of load, so that one would have expected, if variability of load is to blame, a better inaccuracy at the increased output. It may be remarked that no ready means were available for testing the meters on steady load at a higher rate than 750 amperes, and it is therefore possible, though hardly probable, that the motor meter, though correct on half load, was seriously faulty on steady loads at its rated capacity. Or, again, it is possible that stray fields which were insignificant up to about 750 amperes became for some reason very serious at a slightly higher load, though a valid reason for such anomaly is not readily apparent. But whatever the cause, the fact remains that this 1,500-ampere motor meter, tested and apparently quite satisfactory at 600 to 750 amperes steady load, was very appreciably fast when used to measure a tramway load of maximum hanging peak of from 1,200 to 1,500 amperes. Mr. Clark.

Mr. S. W. MELSOM (*in reply*): In reply to Mr. Holden, in the case of meters D and A there was no appreciable change when they were erected slightly out of level, nor did the stray field used affect D and G. Tests made with a 2 or 3 per cent. variation of voltage would not have differed very much from those at normal voltage, the largest difference observed in any of the meters being less than 2 per cent. for a 10 per Mr. Melsom.

Mr. Melsom.

cent. variation of voltage; in the case of a supply voltage one would expect that the small variations from the normal would average out. The case is different, however, where a meter calibrated, say, for a 440-volt circuit, is used at 480 volts.

Mr. Baker raises the question of the actual date at which the meters were dispatched on their journeys. The relative time is shown on the curves Figs. 5 to 10, *i.e.*, at 24·5 and 26·8 weeks respectively; the curves Figs. 11 to 15 were selected without reference to the dates of travelling, but merely as typical of the results obtained during the period which the meters were under test. With regard to the effect of stray fields, the subject is, of course, very indefinite, but it is probable that in a good many cases a fair idea of the extent of the field could be obtained by a study of the distribution of the cables in the vicinity. The rate of the meters was, as Mr. Baker points out, always increased; in some cases, which it was not thought necessary to show in the paper, the current through the experimental coil was reversed and the meter speed was decreased by approximately the same amount. I am wholly in agreement with Mr. Baker on the question of levelling. It seems to be most desirable that meter makers should revert to the old practice of having a plumb-bob or some other arrangement whereby the meter can be levelled from the outside. I should like to express thanks for the complete table of temperature coefficients, which forms a most valuable contribution to the discussion, and would suggest that the "Aron" clock meter, unshunted, which has a negligible temperature coefficient, should be added to the list. I am pleased to find Mr. Baker in agreement regarding the question of the suitability of a meter for a given load, and also as to the accuracy to which tests are normally made. In the case of premises which for several months in the year require only a small portion of the maximum load, it could surely be arranged to install two meters, one being of small size, which could be cut out during the period when the heavier load was required.

It is gratifying to find that Dr. Russell's experience confirms ours so completely. With regard to the effect of vibration, we made some experiments with a small motor running on a bench whereon the meters were erected and found that these particular instruments were only very slightly affected, and that at the lighter loads; in other cases, however, I have observed large differences when meters were subjected to vibration, and quite agree with Dr. Russell that this point should be considered when erecting a meter. In this connection reference might be made to the work of Mr. E. O. Keenan,* who made experiments with motor meters and designed a vibrationless stand which overcame the difficulty.

In reply to Mr. Cridge, the further work described in the Appendix makes it clear that the magnetisation of the spindle does not affect the accuracy of the meter. Regarding his objection to putting meters in

* *Industrie Électrique*, vol. 7, pp. 45–48, 1898; and *Science Abstracts*, vol. 1, No 313, 1898.

Mr. Melsom.

parallel, this method is, I grant, not ideal, but was suggested as an alternative to installing a meter which is far too large for the load for a considerable time. Providing that the meters are of approximately the same resistance, each therefore taking its fair share of the current, there does not seem to be any serious objection to it. The method has been used in somewhat earlier days, and judging from a recent paper* seems to be fairly common practice in America.

I should like to make it quite clear that there was not the least intention of reflecting on the A.E.G. by borrowing a meter of their make from another company. The South Metropolitan Company, who have throughout been interested in the work, kindly offered the loan of a meter of this type which they were not using at the moment, and we very naturally accepted their offer. The meter was in perfect working order, although not quite new, and served the purpose admirably.

Mr. Rennie, in view of his wide experience of meters and meter testing is especially well qualified to criticise a paper on the subject; his appreciative remarks, therefore, are most pleasing to the authors. I quite agree with his suggestion as to publication by makers of characteristic curves of accuracy and information as to temperature coefficient, etc.; in fact, I drew attention to this point in the discussion of Messrs. Ratcliff and Moore's paper.† It is interesting to note that Mr. Rennie considers that a journey to Ireland is most likely to affect the accuracy of a meter. It is probable that this was before motor-cars were in very common use. At the present time, so far as my experience goes, a journey by motor lorry to London is, on account of the shaking, the most severe test one can submit an instrument to. We have, perhaps, been rather more fortunate than the Board of Trade in the condition of the instruments that are sent for test, but in general I think it can safely be said, not only with regard to meters but to nearly all other classes of apparatus, that the general tendency is to ask for a higher degree of accuracy than it is possible to attain with the instrument.

With regard to the question of external appearance, nickel plating, etc., and its effect on the treatment to which a meter is subject, mentioned by Mr. Rennie and by Mr. Roger Smith, while one cannot but agree with these gentlemen it seems rather deplorable that such should be the case. As an alternative to Mr. Rennie's proposal, I would suggest that the engineer should regard his meters as a vital portion of his plant rather than as an artistic addition to his engine-room, purchasing them on the same lines as an experienced smoker buys cigars, *i.e.*, by their quality and without reference to the colour or design of the band. I should like to thank Mr. Roger Smith for giving the curves of the 4,000-ampere-meter inset in his diagram; the difference between the two curves, one obtained when the meter was cold and the other under its normal conditions of working, emphasises strongly the neces-

* F. V. Magalhaes, *Proceedings of the American Institute of Electrical Engineers*, vol. 31, p. 1167, 1912.

† *Journal of the Institution of Electrical Engineers*, vol. 47, p. 3, 1911.

Mr. Melsom.

sity of making tests conform as nearly as possible to normal running conditions. Mr. Roger Smith, in common with Mr. Trotter and Dr. Russell, differs from the opinion expressed in the paper as to the value of tests made in position. I quite agree that very fair results can be obtained with a meter calibrated from time to time in the manner used by Mr. Roger Smith or by a check meter as suggested by Mr. Trotter, with the exception, perhaps, that in the case of disagreement and dispute it would be difficult to convince either party that the check meters were correct and the others were wrong. Mr. Roger Smith's is a very good case, because he has taken care to have his meters properly erected and well cared for. Under such conditions they agree closely with the check meter, and there is no doubt that an accurate record is obtained. I think it may be taken, however, that in general, tests in position are required because the meters to be tested are influenced by stray fields, and in such cases it must be recognised that a check meter will probably be influenced by the stray fields and that a short test, taken possibly when the station is running light, will not indicate the error of the meters under all conditions of running; in fact, a satisfactory test under these conditions involves a thorough investigation of the stray fields in the vicinity of the meters under all conditions of running.

Mr. Young's statement as to the work, both theoretical and practical, that was carried out several years ago by meter makers in order to ascertain whether their meters were suitable for a varying load is very interesting. Since no references are given I presume that the work was not published and would suggest that in this respect Mr. Rennie's remarks *re* publicity might be considered by Mr. Young and those interested in meter manufacture. Mr. Young refers to the effects of stray fields. I think it is clear from the remarks of other speakers in the discussion that stray fields in stations are not necessarily uniform, and that it is advisable to erect even astatic meters out of their influence; neither is it safe to assume that the only stray field that may affect a meter is that produced by the current through its own connecting leads. Durand,* in the paper previously quoted, brings out this point quite strongly. I am very glad to find that Mr. Young is in agreement with the statement as to the possible error in testing, although I should mention that this, under the best conditions, is 0·5 per cent. and not 1 per cent. as he states. It is likely that meter makers have in the past been responsible for a good deal of the misconception that has arisen regarding the accuracy of meter testing. It was no uncommon thing a few years ago to find the error of a meter stated on the maker's certificate, tucked away inside the meter, to an accuracy of one part in ten thousand, while only recently I have seen several cases where the temperature coefficient is stated to one part in a hundred thousand, the last figure involving a measurement of temperature to the one-hundredth part of 1° C.

* *Atti del Congresso Internazionale delle Applicazioni Elettriche, Torino*, 1912, vol. 2, p. 743.

In reply to Mr. Trent, the statement on pages 472 to 474 *re* consistency of meters is, I think, borne out by the curves Figs. 5 to 15, particularly Figs. 5 to 10, where it will be seen that two readings on steady load taken sometimes on the same day did not always agree to within 1 per cent., and that therefore the differences between the constants obtained with the variable loads and those with steady loads (Table I.) are within the limits of errors of observation. The reason for designating the meters by a cipher is fully explained on page 475. I regret that under the circumstances and considering the interests involved it was not possible more clearly to identify the meters in the case of the latter portion of the work. With regard to the question of adapting a meter for a larger load, this is, I recognise, purely a matter of expense. If, as Mr. Trent says, it is cheaper to install a new meter than to change parts of the old one, there is no doubt that this is the better course. If, however, we take the case of a shunted meter of 2,000-ampere capacity where the load is increased to, say, 4,000 amperes, it seems fairly certain that it would be cheaper to install a new shunt and fresh gearing than to purchase a new meter. I think I am right in saying that in each type of meter the gearing is made to a standard size and will fit any meter of the same type, and in this case the change seems to be an operation of little difficulty. Mr. Trent raises the question of tests *in situ*, but I do not agree that stray fields are in any case inherent to the lay-out of the plant. In the great majority of the cases in my experience a comparatively small expenditure on cable would suffice to remove the meters to a safe distance. Taking it, however, that stray fields may be inherent to the lay-out of the plant it is obvious that unless a test *in situ* is carried on under all possible conditions of running and loading of feeders, etc., the result will be of very little value. This point is perhaps more fully dealt with in the reply to Mr. Roger Smith. Mr. Melsom.

Regarding the effect of travelling, the variation in the meter F, shown in Fig. 5, could not definitely be put down to travelling. As stated on page 476, this particular meter was overhauled by the makers, who failed to find any reason for the inconsistency. The effect of stray fields, Figs. 17 to 20, applies to four types of meters, A, B, C, and E. I have dealt with the question of the iron shield in the Appendix. Annealing a cast iron shield only cures the trouble temporarily, and it will be seen that the real solution is not to use cast iron at all for shielding the brake magnets. The question of levelling is referred to in the reply to Mr. Baker.

In reply to Mr. Moore, the question of the magnetisation of the iron shield to protect the brake magnets in motor meters is fully dealt with in the Appendix. It will be seen that it is possible effectively to screen the brake magnets of motor meters. If the variation of rate of the 3,000-ampere meter with the direction of the current, mentioned by Mr. Moore, was the same at all loads, I would suggest that it is due to hysteresis of the iron core in the armature, with which meters of this type are fitted. In the case of the 10-ampere meter of this type there is no iron in the armature, and that is probably the reason why this

Mr. Melsom.

meter was unaffected. I do not suggest that a field from a 1,000-ampere busbar is the maximum to which meters may be subjected, and I am glad to find that Mr. Moore's experience confirms the statement in the paper—that the iron frame on which a switchboard is mounted may produce large fields. The preference for what is called by watchmakers a "chronograph" as distinct from a stop-watch is based mainly on the results of a very large number of severe practical tests made at Kew Observatory on watches of different types. I do not quite know what Mr. Moore would call an "expensive" instrument of this type, but those we have in use are good, and I have found in practice that our chronographs are more accurate than, and quite as reliable as, most stop-watches. I have had no experience with a spring minute-hand, this being always in gear in our watches.

In reply to Mr. McInnes, I have dealt with the question of vibration in the reply to Dr. Russell. With regard to the point raised as to the possibility of testing meters in position, the copper voltameter has always been looked upon as a piece of apparatus that can only be used in a laboratory. The size of the voltameter for currents of 200 amperes and upwards is naturally somewhat large, the requisite arrangements for securing cleanliness and accuracy take a good deal of space, and the whole of the operations require conditions which are not usually obtainable in supply stations. If, however, the question of testing in position by these means were really acute there is no doubt that the difficulties could be overcome. We made some experiments during the progress of the work with a view to evolving a standard electrolytic meter by means of which other meters could be checked. The meters used were of a well-known pattern, one being used with a series resistance, calibrated in milliamperes to integrate the voltage, and the other unshunted to integrate the current. The results obtained with the unshunted meter were very fair, but the shunted meter was not so satisfactory. In spite of this, however, I think that a satisfactory meter of this type might be made and used for the purpose of checking other meters in position.

In reply to Mr. Ratcliff, the size of the meters used for the experiments is quite a usual one for traction circuits. It is true that with large meters used in central stations such troubles as heating and disturbance by stray fields are more marked than in the case of the smaller meters. These points are dealt with in the latter portion of the paper, and apply equally to any size of meter used in station work. For the actual experiments described in the paper meters of 200 amperes suited the purpose admirably, and further there was the question of the copper voltameter, which would have had to be of immense size if currents of over 1,000 amperes had to be measured. As stated in the paper, the meters were, in addition to the tests made with a steady voltage, tested with a varying voltage under actual working conditions in a supply station for a period of three weeks. Fig. 3 shows a fair day's chart of the voltage. With reference to the curves Figs. 5 to 10, the reason that the variation at full and quarter

loads is not always shown in the curves at $\frac{1}{10}$ load is due to the fact that there were far more observations taken at these loads; during the period from four to fourteen weeks no observations were made at $\frac{1}{10}$ load. The points in these curves are joined up, as pointed out in page 485, merely to indicate the changes more clearly and do not necessarily represent the behaviour of the meter during the intervening period. Mr. Ratcliff's remarks on shunted meters are exceedingly interesting and worthy of serious consideration. I am glad to see that he is in agreement on the question of interchangeability of shunts and dial gearing. Errors due to thermal E.M.F. may, as he points out, be guarded against. I think this is really only a question of proper design of the shunt. In Mr. Ratcliff's series of disadvantages of shunted meters, while the effect of shunting Aron meters may be to increase the temperature coefficient, in the case of motor meters this would be, as a rule, decreased, and in this respect shunting would be an advantage. Errors due to contact resistance are perhaps the most important, and these could, I think, be eliminated by an arrangement of lugs whereto the leads connecting the meter to its shunt could be soldered. Mr. Ratcliff suggests that the current through the meter itself should not exceed 5 amperes with a voltage drop of 0·2, but I do not think that any of the commutator type watt-hour meters at present made will work satisfactorily with this current and voltage; the torque would be so very small that variations due to friction would be considerable. I do not agree with Mr. Ratcliff's remarks as to the limitations of the method suggested in the paper for detecting stray fields. According to Campbell * the field of the brake magnets in a B.T.H. meter is about 70 times the field of the armature only, and even if the brake magnets were unshielded it does not seem possible that a stray field could affect them without also affecting the armature when no current was flowing through the main coils. It is difficult to answer the point raised as to the possible errors in testing, as Mr. Ratcliff does not indicate in what respect the errors allowed are excessive. I agree that with deflecting instruments of the best type, frequently calibrated, a rather better accuracy may be obtained, especially if the errors of the two instruments cancel out; this, of course, applies in a smaller degree to measurements made by potentiometer. Another point, however, to be borne in mind in testing large meters is that the direct deflection instruments may be affected by the field produced by the testing circuit, and taking all sources of inaccuracy into consideration the possible error as set out in the paper seems to be quite reasonable. In a great many cases direct deflection instruments will give quite a sufficient degree of accuracy, but where a large meter has to be tested to the best accuracy possible the potentiometer is, in my opinion, much to be preferred. I have referred to the question of watches in reply to Mr. Moore, and have dealt with the effects of momentary overloads in the

Mr. Melsom.

* "The Magnetic Fluxes in Meters and other Electrical Instruments," *Philosophical Magazine*, vol. 47, p. 1, 1899.

Mr. Melsom.

Appendix to the paper. I am glad that Mr. Ratcliff has raised the question of connections. This point might perhaps have been dealt with more fully in the paper, but there is so much that could be said that it probably requires a paper to itself. The present methods of connection are in some cases by no means ideal, and I hope it will be possible at some future time to effect a degree of standardisation of connectors not only for meters but also for other apparatus used to measure large currents.

In reply to Professor Robertson, the figure obtained for the electro-chemical equivalent of copper with a current of 50 amperes differed by only 0·2 per cent. from that at 200 amperes, the deposit at the lower current density being, as would be expected, smaller. A slight variation in the strength of the acid used in the voltameter did not affect the results appreciably, the only difference being that if the acid was too weak the deposit was powdery and could not be collected for weighing. The question of the magnetisation of the spindle of motor meters is dealt with in the Appendix. Professor Robertson's suggestion that a movement of the meter coils, caused by excessive currents, may account for the change of accuracy is, no doubt, correct where the coils are not rigidly supported and are without distance-pieces to keep them apart. In the meter we used there was undoubtedly a movement of the coils when the excessive current was applied, but they drew out again immediately the current was switched off, and we were satisfied that there was no permanent change due to the movement.

Mr. Clark's experience is just the sort of case which caused us to look into the question of the accuracy of meters with a varying load. It is to be noted that the rate of the motor meter, which was the smaller of the two instruments he was observing, increased as the load increased. The probable explanation of the discrepancy is that the 1,500-ampere meter was heated by the current passing through it, and ran faster in consequence. If this were so, tests made on a steady load of 600 amperes would not indicate the error at 1,500 amperes, since the error due to heating at 1,500 amperes would be approximately six times that at 600 amperes. Another factor that may have helped to increase the error is that the temperature coefficient of the motor meter was larger than that of the oscillating meter. It is probable that the temperature of the station was much higher when it was running at full load than when the battery was being charged, and any rise in temperature would tend to make an unshunted motor meter increase in speed.

In concluding this reply, I should like to refer to the paper by Dr. Robertson. His results with a high rate of load variation, particularly the effect of resonance in the Aron meter, are extremely interesting to me, and I hope to be able to find an opportunity of repeating some of them. At the lower rate of current variation his conclusions, with the exception, perhaps, of those relating to mercury meters, agree with ours.

Professor Robertson.

Professor DAVID ROBERTSON (*in reply, communicated*): I shall first deal with one or two points which were raised by more than one speaker. The experiments did not represent practical conditions, and were not intended to do so. On the contrary, they were specially designed so as to be much worse in order that there might be no doubt whatever of the behaviour under any practical load of those meters which showed only small peculiarities in my tests. As this exaggeration of the effects to be expected is very carefully pointed out at the beginning of the discussion of the results of the experiments on page 501, it would seem that some of my most severe critics have not read the paper with that care which the force of their remarks should have required. It was also intended that the experiments should be reproducible, so that anything could be verified if required, and that they should be comparable with any future experiments carried out in a similar manner. Practical conditions are so very indefinite that it is impossible to do more than guess at a numerical measure of the amount of exaggeration, but I believe that the discrepancies were all magnified at least ten times, and some of them much more than this, in particular the resonance effect with the Aron meter, which is only produced within a very narrow range of load frequency, and not at all under ordinary circumstances.

Paragraph 2 of the "General Conclusions" on page 508 seems to have conveyed to many members the meaning of an entire condemnation of mercury meters. This was very far from my intention, and indeed I drew special attention to the merits of certain meters of this kind when discussing Fig. 9. This paragraph gives the typical variable load effects of meters of this class, and points out the necessity of having each type and size tested before we can be quite certain of its behaviour on variable loads. It does not say that the error is in all, or even in most, cases great enough to be of any practical importance, and is not even inconsistent with it becoming vanishingly small in some particular case. If, quite apart from the theory, Figs. 8 and 9, giving the results of tests on instruments by makers who have had the greatest experience of this type, cannot be said to justify my conclusion, it is difficult to imagine what would be necessary. Bearing in mind the exaggeration already referred to, it would not appear that the errors shown by the modern types of meters on these figures are of any practical importance, but at the same time it is very probable that the two obsolete ones would not be suitable for a rapidly variable load.

My assumptions regarding the laws of fluid friction are based on the classical experiments of Osborne Reynolds, which I find are also mentioned in the article to which Mr. Trotter refers, which adds the additional interesting statement that the friction at the place where mercury, metal, and air meet follows approximately the solid friction law. Reynolds' experiments showed that the change from the linear to the quadratic law takes place suddenly at a certain critical speed, which is very low except with very viscous liquids, and which increases with the viscosity and with the smallness of the clearances. The difference

Professor Robertson.

between my critics and myself on this point is thus narrowed down to a question as to whether actual meters run below or above the critical speed beyond which the square law applies, and my answer is that the best known mercury meters always have compensating coils, which would be worse than useless if the fluid friction followed the linear law. The difficulty of keeping the working speed below the critical point is due to the small effectiveness of the brake disk at very low speeds, and the consequent greater importance of the friction of the pivots and gearing, particularly the latter in a mercury meter. I was not aware that the B.T.H. Company had a mercury meter in which fluid friction compensation was unnecessary or I should certainly have asked for one to include in the tests. If the fluid friction effect on steady load is very small without any compensation, then it will also be very small on variable load. Below the critical speed the fluid friction follows the same law as the eddy brake, and is included with it in the mathematical theory. The quadratic term and the errors which arise from it entirely disappear. That part of the control due to viscosity thus produces no direct error, but it changes with temperature much more than the eddy brake torque, and in the same way. At a sufficiently small load any mercury meter could be run below the critical speed, but then the fluid friction is of so little importance that it does not matter what law it follows as it diminishes further. For mathematical theories it is always necessary to deal with ideal conditions which only approximately represent the real ones; they may only be feeble lights to help us on our way, but the guidance is certainly better than having to grope in the dark.

The statement on page 512 that the starting and stopping error is infinite with an ideal fluid friction meter is quite correct, and can be more easily proved by working out this case by itself instead of deriving it from the general law. Thus the equation for stopping is:—

$$\mathrm{K}\ddot{\theta} + k_{r_2}\dot{\theta}^2 = 0,$$

or—

$$\mathrm{T}_{0_2}\ddot{\theta}\,\dot{\theta}_{\mathrm{S}} + \dot{\theta}^2 = 0,$$

where—

$$\mathrm{T}_{0_2} = \frac{\mathrm{K}}{k_{r_2}\dot{\theta}_{\mathrm{S}}} = \frac{\mathrm{K}\dot{\theta}_{\mathrm{S}}}{k_{r_2}\dot{\theta}_{\mathrm{S}}^2} = \frac{\text{angular momentum at speed } \dot{\theta}_{\mathrm{S}}}{\text{fluid friction torque at that speed}}.$$

With the initial speed $= \dot{\theta}_{\mathrm{S}}$, the solution is—

$$\dot{\theta} = \frac{\mathrm{T}_{0_2}}{\mathrm{T} + \mathrm{T}_{0_2}}\dot{\theta}_{\mathrm{S}},$$

which does not become zero until T is infinite. And—

$$\theta = \mathrm{T}_{0_2}\dot{\theta}_{\mathrm{S}} \log \frac{\mathrm{T} + \mathrm{T}_{0_2}}{\mathrm{T}_{0_2}},$$

which is infinite when T is infinite.

There are two ways in which b may become infinite. In the first,

Professor Robertson.

to which Dr. Russell's figures apply, the fluid friction becomes infinitely great, while the eddy brake torque and T_0 remain finite. But infinitely great forces can hardly represent any actual meter. In the other way, for which my statement holds, b becomes infinite by the diminution of the eddy brake torque to zero, while the fluid friction remains finite. T_0 thus becomes infinite along with b, but T_0/b remains finite, being the time taken for the rotor to come to rest from the standard speed under the action of a constant resisting torque equal to b times the eddy brake torque—that is, equal to the finite fluid friction torque—at that speed.

I do not quite understand what Mr. Rennie had in his mind when he referred to the "very unsafe method" by which the plates are attached in my voltameter, and indeed I think his remarks on this point are at least ungenerous, seeing that he has never seen my cell nor even discussed it with any one who saw it actually used. The construction is eminently "safe" and on engineering, as distinct from physical, lines; it is much safer than any form of clip or spring contact, and has also the advantage of requiring only flat plates. If Mr. Rennie has in his mind possible damage to the plates while undoing the nuts (milled heads might actually have been better for this size, but hexagonal brass nuts were available in stock) then he need have no fear, for they were on the hard part of the plates where they are not acted on by the liquid. There is certainly no more danger, and probably less, from the nuts in my form than from the guide-blocks in the N.P.L. cell, which, so far as I can judge from the photograph, rub on the edges of the plates, the very place where the deposit is most easily abraded. I can assure Mr. Rennie that my two cathodes are very easily removed without even the danger of soiling one's fingers, and that my voltameter was also "admirably suited to its purpose." The excellent device of blowing air into the liquid which was used by Messrs. Eastland and Melsom would have been of no value with my small currents, but would be a useful addition when dealing with larger ones.

Most members of the Institution will, I think, prefer the straightforward method of stating which results apply to each meter. Indeed, it is difficult to see how they can otherwise be of any use to any one who does not possess the key to the cipher, except in those cases in which the results are of a purely negative kind. I do not think that the secret method is at all fair to those who have lent instruments for the tests, as all the meters are laid open to the suspicion of any undesirable characteristics exhibited by any one of their number, and I did not, in fact, find any of the makers averse to having the curves labelled, even after they knew how their meters had behaved in my tests. Mr. Rennie's bogey of the inquisitive consumer has already been conjured up before me, but the other performer was more logical, and put it forward as a reason for suppressing the results altogether. If this hypothetical payer of electrical accounts were to come across either Figs. 8 or 13 without the names, he would still be in the uncomfortable condition which troubles Mr. Rennie, whatever type of meter

Professor Robertson.

was in use on his premises, for he would be quite certain that one of these curves applied to the particular instrument with which he was familiar, and that it explained the large discrepancy which always occurred between the amount of his bills and the sum he thought he should have to pay.

Mr. Young's letter will acquit meter manufacturers of the ignorance of the elements of the theoretical side of meters which Mr. Rennie almost suggests is their condition. But there is really no case to answer, for it is common knowledge that they do use compensating coils on watt-hour meters whose action depends on the assumption of constant solid friction, and that the two principal manufacturers of mercury meters have issued handsome descriptive catalogues containing excellent disquisitions on the laws of fluid friction. If fluid friction were to follow no fixed law, as Mr. Rennie suggests, motor meters would be impossible unless it could at least be kept within very small limits. It is the erratic variation of solid friction which makes it impossible to do more than roughly compensate it, and which renders it so necessary to reduce the effects of solid friction by swamping it by a large eddy brake torque.

It should be noted that Mr. Smith does not use the term "fluid friction meter" in the same sense as I have employed it in the paper, but that he refers to watt-hour meters which would fall into the same class, from our point of view, as those on Fig. 9, not Fig. 8.

Mr. Young gives the simplest possible proof of the correctness on variable loads of an ideal eddy-current brake meter, but this form of the theory gives no information as to the effects of actual departures from the ideal conditions. The more complete theory given in the appendix to my paper takes account of the simplest of these departures, and *does* give the explanation of the difference between the behaviour of mercury and commutator meters, which is shown by my curves. I am not quite clear which paragraph Mr. Young takes such strong exception to, as I have said nothing at all about variations with time, *per se*, but I presume he must refer to the part of page 508 where the permanent effects of heavy overloads are discussed. In that case I would refer him to page 500 of Messrs. Melsom and Eastland's paper and to the remarks of Mr. Moore and Mr. Ratcliffe.

The primary effects of changes of voltage are the same as those of variations of current, but discrepancies between the two methods of testing would probably arise owing to local heating, local strains, and local eddy currents. In particular, the change of resistance of the armature circuit with different voltages does produce appreciable effects on the rate of the meter. The phase-difference effect mentioned by Mr. Ratcliffe could only arise if the time constant of one of the circuits of the meter (volt coil, main coils, and external shunt) were comparable with the intervals of time at which the load changed; it does not seem that this is likely to be the case even with a very rapidly fluctuating load. Actually, the meters of Fig. 10 were shunted meters, but these curves show no features which could be attributed to a difference between the inductance of the shunt and that of the armature.

THE CORRUGATION OF RAILS.

By Professor ALFRED SCHWARTZ, Member, and R. G. CUNLIFFE, M.Sc.Tech., Associate Member.

(*Paper received 2nd March, received in final form 18th March, and read before the* MANCHESTER LOCAL SECTION *on 26th March*, 1912.)

SUMMARY.

I. INTRODUCTION.

A careful survey of the literature on rail corrugation shows that while much has been written on the subject during the past ten years, the conclusions have been based upon observations which have been restricted almost entirely to the processes employed, and the results obtained in rolling and straightening the rails, and to observations on the tramway track and rolling stock under service conditions.

While an accurate knowledge of the facts concerning corrugation gleaned under service conditions is a necessary preliminary to the solution of the problem, the authors hold that owing to the large number of variables present in actual practice, the problem can best be attacked by experimenting in the laboratory under conditions which can be carefully controlled, and by correlating the results thus obtained with those found under service conditions.

The authors are fully aware of the limitations attaching to laboratory experiments, and can only hope that some of the devices employed, and the results obtained by them, may prove of service to the tramway engineers, with whom the ultimate solution of the problem of corrugation must remain.

II. Definition of Terms.

Note.—The terms marked with an asterisk are as defined by the Corrugation Sub-Committee of the Municipal Tramways Association.

1. A wheel is said to "roll" when the point of contact of the wheel with the rail at any instant progresses along the rail with a speed equal to the peripheral speed of the wheel at that instant.

*2. A wheel is said to "skid" when a point on the periphery of the wheel comes in contact with successive points on the rail.

*3. A wheel is said to "slip" when successive points on the periphery of the wheel come in contact with the same point on the rail.

*4. A wheel is said to "slide" when it moves laterally across the rail.

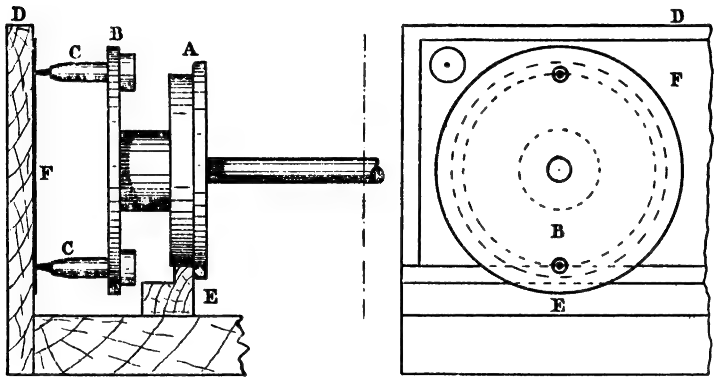


Fig. 1.

*5. A wheel is said to "crowd" when it is being continuously deviated from the line in which it would travel if free by the flange of the wheel pressing against the rail.

6. A wheel is said to "jump" when the pressure between the wheel tyre and the rail tread is variable under constant load.

7. Corrugation is said to be present when the surface in question exhibits a series of alternate crests and hollows.

III. Experiments with Model Car and Track.

The experiments described in this section were carried out for the authors by Messrs. W. Grant, H. J. Gwyther, and S. E. W. Taylor, and were undertaken with a view to affording some indication of the extent to which "slip" and "skid" take place with trailed wheels under various conditions of load and track.

A model Brill truck to a scale of $\frac{1}{20}$ was employed with a recording

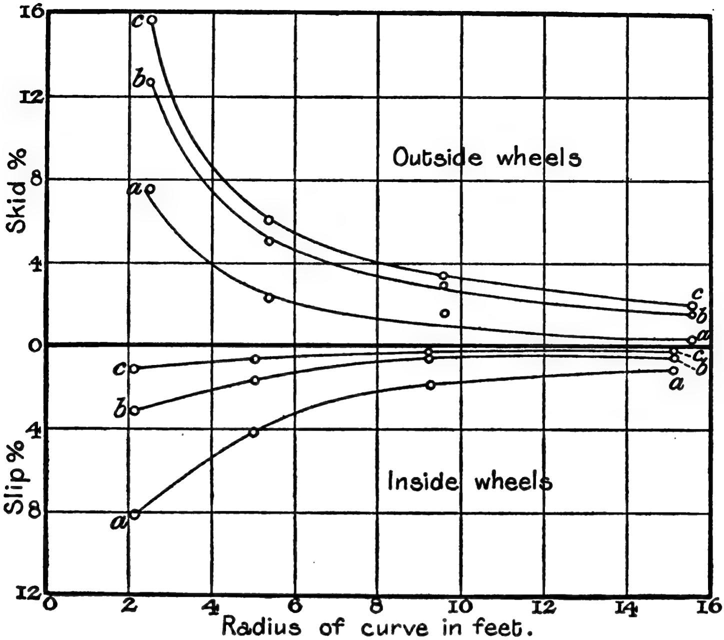


FIG. 2.—Slip and Skid of Wheels of Equal Diameter on Curves of various Radius.

(*a*) Weight over outside wheels. (*b*) Weight over centre line of truck. (*c*) Weight over inside wheels.

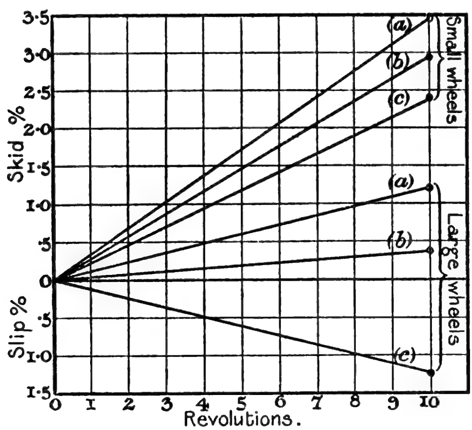


FIG. 3.—Slip and Skid of Wheels of unequal Diameters on a Straight Track with a Weight of 8 lbs. placed.

(*a* Over the large wheels. *b*) Over the centre line of the truck. (*c*) Over the small wheels.

device, as shown in Fig 1, where A represents one of the running wheels of the car with square throat and tread resting on a wood rail E, without groove or lip, the wheels being fixed to the axles. A disc B, carrying two spring pencil-holders C, is fixed to an extension of the wheel axle. The pencils are spaced 180° apart, and at a distance from the centre line of the axle equal to the rolling radius of the wheel. When the car is in position on the rails, the pencils in the spring-holders are in contact with a paper strip F fastened to a vertical wood board D, which is parallel to the rails. As the wheels rotate, the pencils trace cycloidal curves on the paper along both sides of the track, and a comparison of the curves traced in this way with the true cycloidal curves proper to the wheel diameter in question shows to what extent slip or skid has taken place in each revolution.

In this way it was found that on curves from 2 to 15 ft. radius the increment of slip or skid per revolution was practically constant for a given curve.

Experiment No. 1.—In order to determine the effect of a load in various positions on the car when passing round curves, a weight of 8 lbs. was employed with its long axis in the following positions on curves :—

(*a*) Vertically over the outside wheels of car.
(*b*) Vertically over the centre line of car.
(*c*) Vertically over inside wheels of car.

The results obtained with wheels of equal diameters passing round curves of 2 to 15 ft. radius are shown in Fig. 2, the slip and skid respectively being expressed as a percentage of the distance which would have been traversed by the wheel in question with a pure rolling motion.

In this and subsequent experiments the slip and skid were determined by the distance traversed on the rail by a point on the periphery of the wheel in a given number of revolutions.

Experiment No. 2.—Wheels of unequal diameters were now employed, those on one side of the car being 2¾ per cent. greater in diameter than those on the other side, these are referred to as "large" and "small" wheels respectively; the results obtained on straight track are shown in Fig. 3.

Experiment No. 3.—The wheels of unequal diameters employed in Experiment No. 2 were now used on curves of radius of 2 to 15 ft., and the results obtained compared with those of wheels of equal diameter are given in Table I.

In the experiments detailed above, measurements of skid and slip were made on the back pair of wheels on the truck. It was, however, found that on the front pair of wheels the percentage skid on the outer wheel was greater, and the percentage slip on the inner wheel was less than on the corresponding wheels of the back pair.

With wheels of unequal diameters on curves of various radius (the

TABLE I.

Slip and skid on curves with wheels of unequal and equal diameters; diameters of "large wheels" $2\frac{3}{4}$ per cent. greater than that of "small wheels"; the weight of 8 lbs. in the three positions specified under Experiment No 1. The terms "outside" and "inside" apply to the outer and inner rails of the curves respectively.

	Skid. Outside Wheels.				Slip. Inside Wheels.			
	Radius of Curve in Feet.							
	2.	5.	9.	15.	2.	5.	9.	15.
Weight on Outside (*a*).								
Large wheels outside, small inside ...	9·8	2·4	1·5	1·2	3·8	1·4	0·0	1·4*
Even wheels	7·5	2·3	1·5	0·2	8·2	4·2	2·0	1·2
Small wheels outside, large inside ...	9·6	5·3	4·0	2·8	7·6	4·0	2·2	1·2
Weight in Middle (*b*).								
Large wheels outside, small inside ...	12·0	2·4	9·0	1·0	0·5*	0·4	0·4*	0·8*
Even wheels	12·6	5·0	2·8	0·7	3·2	1·7	0·5	0·6
Small wheels outside, large inside ...	17·4	8·4	5·7	4·0	2·6	1·4	0·5	1·0
Weight on Inside (*c*).								
Large wheels outside, small inside ...	15·1	3·4	1·4	0·0	2·0	1·0	0·0	1·0*
Even wheels	15·6	6·0	3·3	1·8	1·0	0·8	0·3	0·3
Small wheels outside, large inside ...	20·5	9·3	6·4	4·8	0·1	0·5	0·3	0·3

* In this case the figure represents "skid."

smaller wheels being inside) we may consider three theoretical cases as follows :—

Case I.—If the radius of the curve be equal to the height of the cone represented by the pair of wheels of unequal diameters, then the inside and outside wheels will pass round the curve without slip or skid.

Case II.—If the radius of the curve be less than the height of the cone represented by the wheels, let l_i = the length of path to be traversed by the inside wheels, and l_o = the length of path to be traversed by the outside wheels, then since $\frac{l_i}{l_o}$ is less than in Case I., the inside wheel will tend to slip and the outside wheel to skid.

Case III.—If the radius of the curve be greater than the height of the cone represented by the wheels, then $\frac{l_i}{l_o}$ will be greater than in Case I.—that is to say, the distance to be traversed by the inside wheel as compared with that to be traversed by the outside wheel, will be less than in Case I. The inside wheel will therefore tend to skid and the outside wheel to slip.

With regard to the simultaneous occurrence of skid on both wheels, with a truck that is trailed along the track, this is probably due to the action of the flange, and its tendency to mount the outer rail of the curve, thus increasing the rolling diameter of the wheel. The skidding effect introduced by flange action may be greater than the slipping effect under normal conditions, and thus produce skidding on both wheels simultaneously.

The following conclusions may be drawn from the foregoing experiments :—

Equal Wheels on Curved Track.

(*a*) Both skid and slip diminish as the radius of the curve increases.

(*b*) The skid and slip of a wheel diminish as the pressure upon the wheel is increased.

(*c*) In every case the skid of a wheel on the outer rail of a curve is greater than the slip on its mate wheel ; this is due to the additional skid produced by the action of the flange.

Unequal Wheels on Curved Track.

(*a*) The maximum skid and slip occur when the larger wheels are on the inner rail of the curve.

(*b*) The minimum skid and slip occur when the smaller wheels are on the inner rail of the curve.

(*c*) The conclusions given above (under *a*, *b*, and *c*) for equal wheels on curved track hold good also for unequal wheels on curves.

IV. Experiments on the Cold Flow of Metals due to Rubbing and Hammering.

The experiments in this section were directed to the determination of the effects produced by unlubricated and lubricated rubbing friction upon various surfaces.

Experiment No. 4.—A cast lead disc A (see Fig. 4) 9 in. in diameter and 1 in. thick was turned true in a lathe on the sides and edges. A brass cylinder B 1 in. in diameter and 2 in. long was pinned to one end of a steel arm C, 6 in. long, in such a way that the cylinder could not rotate. The other extremity of the arm was mounted on an axle D, the bearings for which were bolted to the slide rest of the lathe. The arm C was adjusted so that when it was horizontal the cylinder rested upon the edge of the lead disc with the centre of the cylinder vertically above the centre of the disc, the cylinder B being free to rise and fall in an arc about the axis D as centre.

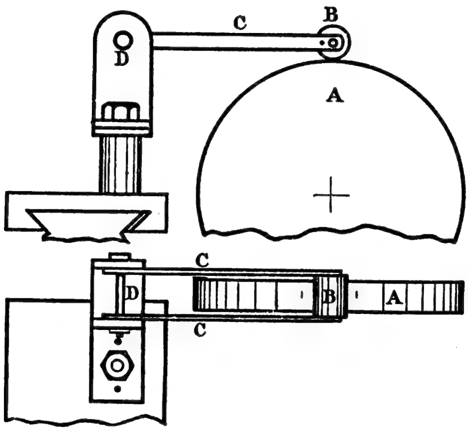


Fig. 4.

The disc was then rotated in the lathe at a peripheral speed of 10 miles per hour. After running in this way for a short time, it was found that the cylinder appeared to be "floating" above the edge of the disc, the gap between the cylinder and the disc being marked by a persistent line of light. This effect was produced by the rapid rise and fall of the cylinder in its passage over the minute irregularities on the surface of the disc.

This floating action was found to exist even when the edge of the disc had been carefully polished with flour emery; its amplitude rapidly increased as the experiment progressed, and finally resulted in the cylinder movement resolving itself into a series of jumps, the average

height of these jumps at the conclusion of the experiments being about 3 to 4 in. above the surface of the disc.

After running for a few minutes, the edge of the disc was found to be covered with a number of abrasions of somewhat irregular pitch. These abrasions were formed by the surface of the metal being pushed forward in certain places, thus forming slight elevations or ridges which were perceptible to sight and touch. In consequence of these ridges the jumping of the cylinder now became considerable, and the surface of the metal was rapidly displaced owing to the hammering produced by the successive blows of the cylinder. This action was continued until the edge of the disc was strongly marked with corrugation of somewhat irregular pitch.

In order to record the pitch and form of the corrugation in its various stages of growth, the following procedure was adopted: A narrow band of thin tough paper was placed closely round the edge of the disc; the ends of the band were allowed to overlap slightly, and were fastened together with glue. A piece of hard wood about 4 in. long and an inch thick was shaped to fit the periphery of the lead disc, and its concave surface was coated with blacklead. The wood sector was then rubbed over the top surface of the paper band when in position on the lead disc, much in the same way as "heelball" is used in rubbing a monumental brass. In this way the paper above all the high points or crests on the lead disc received a coating of blacklead, while the hollows remained untouched.

Fig. 5 shows three such records from a disc of lead, the first, A, obtained after 10 minutes' run at a peripheral speed of 10 miles per hour, while B and C show the size to which the corrugations had grown after runs of half an hour and two hours, respectively, at the same speed.

Fig. 6 is a photographic reproduction of a lead ring, the divisions of which show the aspect of the corrugation in its various stages of growth. For the purposes of reproduction, the lead ring has been split longitudinally and flattened out.

Experiment No. 5.—The fixed rubbing cylinder—(B) Fig. 4—was now replaced by a cylinder of the same diameter, which was capable of rotating freely on an axle. The final result obtained with this cylinder is shown in Fig. 6 (E). The time occupied in obtaining corrugation of a given size was very much longer with the rotating cylinder than with the fixed one.

Experiment No. 6.—It was decided to cause the rubbing cylinder to jump once in each revolution by placing an artificial obstacle on the edge of the disc. This took the form of a tapered insert of brass 1 in. in length, and of the same width as the lead disc, the leading edge of the insert was flush with the surface of the disc, while the trailing edge was $\frac{1}{16}$ in. above the disc surface.

Fig. 7 shows a consecutive series of rubbings from this disc. The position of the trailing edge of the insert is marked by a vertical line on the left side of the diagram, and from this point a jump took place in

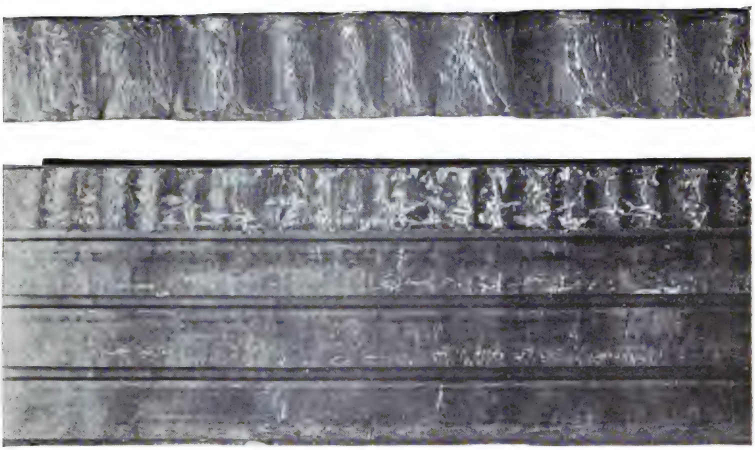
A

B

C

FIG. 5.—Graphite Records of Corrugation from a Lead Disc running at a Peripheral Speed of 10 Miles per Hour with a smooth Brass Cylinder resting upon it.

A after 10 minutes. **B** after 30 minutes. **C** after 120 minutes. (Experiment No. 4.)
(Scale, 12 mm. = 1 in.)



E

D

C

B

A

FIG. 6.—Lead Rings turned from the Discs experimented upon, split and flattened for the purposes of Reproduction to illustrate Stages in the Growth of the Corrugation.

A after 30 minutes. **B** after 1 hour. **C** after 2 hours. **D** after 4 hours. (Experiment No. 4.
E after 50 hours (separate specimen) brass cylinder free to rotate. (Experiment No. 5.)

(Scale, 8 mm = 1 in.)

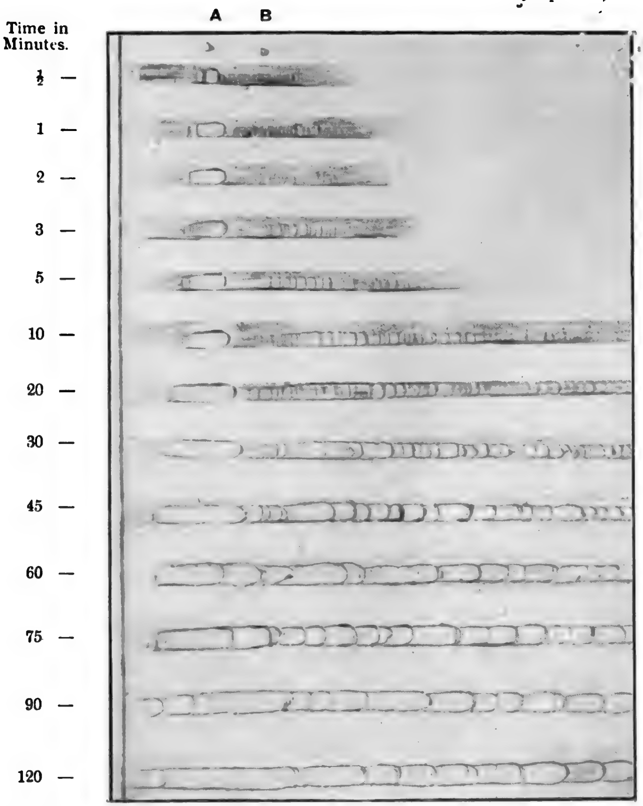


FIG. 7.—Consecutive Series of Graphite Records from a Lead Disc, the Rubbing Cylinder jumping once in each Revolution over an Obstacle $\frac{1}{16}$ in. high inserted for this purpose.

Peripheral speed, 10 miles per hour. (Experiment No. 6.)
(Scale, 9 mm. = 1 in.)

each revolution, since the speed of the disc was such that the upward velocity given to the cylinder was sufficient to cause the latter to break contact with the disc.

The deep indentation caused by the rubbing cylinder striking the disc immediately after its jump is clearly shown at A in the first record; the smaller indentations at B are due to the vibrations set up in the arm on which the rubbing cylinder is carried.

Experiment No. 7.—The rubbing cylinder was removed from the pivoted arm previously employed and mounted over the centre of the lead disc. The ends of the cylinder were filed to rectangular section and rested in two slots, which prevented the cylinder from rotating, but allowed it to move vertically for about an inch. The same floating effect was observed with this cylinder as in previous experiments,

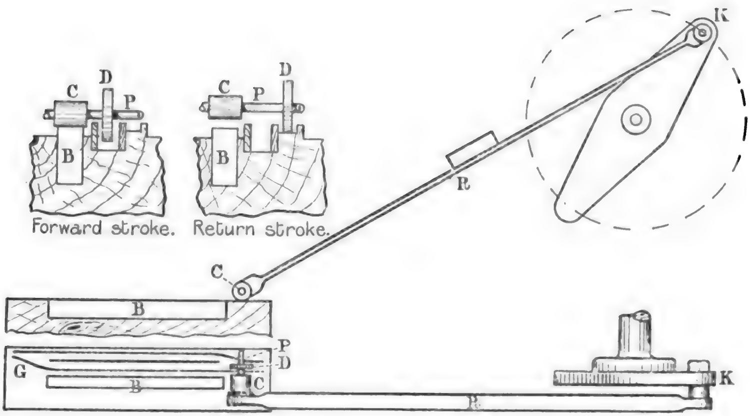


FIG. 8.

and the amplitude of the jumps increased as the experiment proceeded until they were limited by the length of the slots.

Experiment No. 8.—The cylinder was free to revolve on the end of a pivoted arm 9 in. long, and was driven by means of a belt at a peripheral speed higher than that of the disc upon which it rested. Corrugation appeared very slowly, and varied in form from time to time as the position of the surface of contact between the cylinder and the disc shifted on the surface of the disc edge. Distinct flow of the metal occurred and shallow corrugation was produced, but there was little or no jumping and hammering action developed.

Experiment No. 9.—A straight bar of cast lead carefully machined on the sides and edges was employed, and arrangements were made whereby the bar was rubbed in one direction only by a steel cylinder which did not rotate.

Details of the arrangements are shown in Fig. 8. The steel rubbing

cylinder C was fixed to one end of an iron connecting rod R of rectangular section, the other end of which was attached to a crank K. A steel disc D was mounted free on a pin P in the cylinder C. The lead bar B, which was 2 ft. long, 1 in. wide, and 2 in. deep, was securely clamped throughout its length to a heavy cast-iron base fixed to the floor. On the forward stroke the cylinder rested upon the surface of the lead bar, and the disc D made no contact with the base. On the completion of the forward stroke the disc D was shifted to the outer end of the pin P by means of small guides G, so that on the return stroke it ran upon a wood rail fixed to the base at such a height that the rubbing cylinder was lifted clear of the lead bar. At the end of the return stroke, a further set of guides replaced the disc in its original position on the pin. A velocity diagram was constructed, which showed with a constant crank speed the variation in speed of the cylinder in various positions on the lead bar.

With a crank speed of 236 ft. per minute, which was employed in this and subsequent experiments (unless otherwise stated), the speeds of the rubbing cylinder were as follows:—

1. At leading end of lead bar, 166 ft. per minute.
2. At centre of lead bar, 274 ft. per minute.
3. At far end of lead bar, 186 ft. per minute.

Fig. 9 A, B, C, and D show a series of rubbings arranged in chronological order obtained from strips of paper laid upon the lead bar, and rubbed longitudinally on their upper surfaces with a flat piece of hard wood, the under surface of which had been coated with black-lead. In this case the short axis of the connecting rod was horizontal, and the rod was weighted at the centre. It will be observed that after 3 minutes' rubbing with the fixed cylinder the surface of the lead bar is covered with corrugation of short pitch, and that as the rubbing proceeds the pitch and depth of the corrugation progressively increase. The addition of a weight of 5 lbs. to the centre of the connecting rod considerably increased the rate of growth of the corrugation.

Experiment No. 10.—The conditions of this experiment were the same as those of the previous one, except that the rubbing cylinder and the lead bar were well lubricated with oil throughout the experiment. The results obtained are shown in Fig. 9 (E, F, and G), the paper rubbings being taken at time intervals corresponding with those in the previous experiment, in which the bar was unlubricated. The initial corrugation appeared after a few strokes of the rubbing cylinder, and it is much of the same initial pitch as that in the previous experiment, although the corrugation itself is not quite so well marked. The corrugation formed first towards the far end of the bar and spread later to the leading end, the pitch increased slowly with time, but after the lapse of nearly an hour it was still extremely small compared with the results obtained without lubrication.

Experiment No. 11.—A steel cylinder capable of rotating freely on a steel axle was substituted for the fixed rubbing cylinder, and results were obtained—Fig. 10 (A)—identical in their main features with those obtained with the fixed rubbing cylinder under similar conditions—Fig. 10 (B). The time required to produce corrugation of a given size was, however, very much longer in the case of the cylinder that was free to rotate than that required with the fixed cylinder.

Experiment No. 12.—The stroke of the machine was altered so that the fixed rubbing cylinder was trailed over the surface of the lead bar from the far end of the bar on the return stroke, in place of being pushed forward on the outward stroke, as in the previous experiments. The results obtained are shown in Fig. 10 (D). It will be seen that the bar is heavily corrugated, but the crests of the corrugation do not seem to be so pronounced as in the previous experiments.

Experiment No. 13.—An artificial jump was arranged at the leading end of the lead bar by inserting a piece of rectangular steel ½ in. thick and of the same width as the bar. The top edge of this steel insert was rounded on the side on which the fixed rubbing cylinder approached it, and was ¼ in. above the surface of the lead bar. Fig. 10 (C) shows the result obtained with the short axis of the connecting rod flat and a weight of 5 lbs. at the centre of the rod.

In the case of lead the metal is pushed forward, and piled up in front of the point of impact, and the tops of the crests thus formed are higher than the original surface of the bar. The hollows are lower than the original surface of the bar owing to metal having been pushed forward from them to form the crests, and to fins of metal being extruded at the sides of the bar due to the hammering of the cylinder.

With lead it was found that there was a limit to the height to which the crests were raised above the original surface of the rail, since after a certain point was reached there was not sufficient cohesion between the various layers of metal which had been pushed forward, to hold them in position, and large and small flakes were removed at frequent intervals by the rubbing cylinder.

Reverting to Fig 10 (C), we find that the first three corrugations are of longer pitch and are deeper than the others on account of the action of the artificial jump. Consider now the phase of the vibration of the connecting rod at the moment that the rubbing cylinder is on the top of the steel insert—it may be such as to add to the upward velocity imparted to the rubbing cylinder on its being driven over the obstacle, or it may be acting in opposition to this velocity; with, of course, numerous intermediate values within these limits. In the first case, the length of the jump taken by the rubbing cylinder will be a maximum, while in the second case it will be a minimum. It is within these limits that the blows from the cylinder will fall. This matter will be discussed further in Sections VI. and VII., and is only here referred to as leading up to the next experiment.

Experiment No. 14.—The long axis of the rubbing cylinder which had hitherto been arranged to be at right angles to the long axis of the lead bar was now altered by bending back the free end of the rubbing cylinder so that the axis of the cylinder made an angle of 30° with the bar. It was found that the corrugations produced followed the angle of inclination of the cylinder. Further that the metal was extruded in the form of thin flakes on the edge of the bar under the free end of the cylinder—that is to say, on the side of the bar towards which the rubbing cylinder now faced. The corrugation did not grow nearly so rapidly as in the previous experiments, the height attained by the crests in a given time being considerably reduced, due doubtless to the extrusion of the metal at the side of the bar in place of its displacement longitudinally and the consequent reduction in the jumping action of the cylinder.

The inclined rubbing cylinder was next removed and replaced by a cone, the taper of which was 1 in 12, attached to the connecting rod at its base with its long axis at right angles to the long axis of the lead bar. The corrugation produced was at right angles to the long axis of the bar, and was of normal type except, of course, that it commenced on the edge of the bar under the base of the cone. The specimens are exhibited.

Experiment No. 15.—A bar of yellow pine was selected with a view to trying the effect of an artificial jump on a material, the surface of which did not lend itself readily to horizontal displacement, and yet would be sufficiently soft to show the effect of hammering. The arrangement of the apparatus was the same as in experiment No. 13, but the top surface of the steel obstacle was smeared with a mixture of blacklead and oil, which was taken up by the underside of the rubbing cylinder each time it passed over the obstacle and deposited on the wood bar at the point where the cylinder struck it. The result is shown in Fig. 11 (A), where the black patches represent the areas within which the blows fell, while the white patches represent the areas which were not touched by the cylinder. The black areas will ultimately become hollows, while the white areas will be crests, the tops of which coincide with the original surface of the bar. The experiment was continued, and the final result obtained is shown in Fig. 11 (B). At the conclusion of the experiment, and for the purposes of reproduction, the whole surface of the wood bar was coated with blacklead, the bar was then rubbed face downwards on a sheet of fine glass-paper placed upon a surface plate; this picked out the crests in white, leaving the hollows black.

The hollows of corrugations Nos. 2, 3, 4, etc., will, in their initial stages, be beaten out within the limits already referred to; but as the experiment proceeds, and corrugation No. 1 begins to gain in depth, a new set of conditions will be set up. The jump for corrugation No. 2 has to be made from some point in the hollow of corrugation No. 1, and the varying conditions of this, in conjunction with the phase of the vibration of the connecting rod, will modify the form of corrugation

No. 2. This reasoning applies to the succeeding corrugations on the wood bar.

Experiment No. 16.—The rubbing cylinder was fixed at the end of the iron connecting rod, the short axis of which was vertical without weight at centre, and no artificial jump was used. The final result obtained on a wood bar after a run of 120 hours is shown in Fig. 11 (C).

In this case it would appear that the hollows of the corrugations have been beaten out within the limits set by the transverse vibrations of the connecting rod, the crests remaining at the level of the original surface of the bar. This figure is also of interest in that the rubbing cylinder was, to begin with, only bearing on one edge of the wood bar, and as the hollows increased in depth the bearing of the cylinder was increased until it extended right across the bar at the deepest parts of the hollows. This same formation is frequently found in corrugation on the track.

Experiment No. 17.—A bar of plaster of Paris was employed, the surface of which had been treated with shellac to harden it. The results obtained in the initial stages showed fine corrugation with a pitch of 8 to the inch.

Experiment No. 18.—In this experiment a bar of untreated plaster was employed, which disintegrated rather than suffer longitudinal displacement. The result attained in 5 minutes is shown in Fig 11 (D).

Experiment No. 19.—In the previous experiments the angle which the connecting rod made with the lead bar at the commencement of its stroke was 26°, and at the far end of the bar the angle was 19°. It was now arranged that the angle of the rod was 8¼° at the commencement of the stroke, and 4° at the end. The result showed a very marked diminution in the corrugation with the low angle of approach. The results are shown in Fig. 11 (E and F).

Experiment No. 20.—In the previous experiments the average speed of the rubbing cylinder was 200 ft. per minute, this was now reduced to 80 ft. per minute, with the result that the corrugation developed more slowly, and was very much altered in character. The pitch increased with time, but the amplitude of the corrugation did not increase proportionately, and remained extremely small. The specimens are exhibited.

Experiment No. 21.—In the previous experiments the iron connecting rod was 6 ft. long × 1⅝ × ¼ in., this was replaced successively by a wood bar 6 ft. × 6 in. × 1 in., and 3 ft. × 6 in. × 2 in. with the short axis vertical in each case. The initial corrugation produced after a run of 2½ minutes was practically the same in each case.

Experiment No. 22.—In order to show that actual jumping of the rubbing cylinder takes place on its passage over the corrugation, a continuous line was scribed along the centre line of the bar, and on the surface of the corrugation. The rubbing with the cylinder was then continued, and it was found that the scribed line was obliterated on the leading side of the crests only, and that it remained intact in the hollows for a considerable time.

V. Methods of Experiment and Observation on the Tramway Track.

Profile Apparatus.—A portable apparatus was constructed for obtaining longitudinal profiles of corrugations with a vertical magnification of 10 to 40 times and a natural horizontal scale.

By this means it was found that the corrugation was, in general, irregular both as to pitch and amplitude, and that the crests of the corrugations were at the general level of the rail head, while the hollows were below this level.

Plaster Casts.—Plaster casts of corrugation were obtained from the rails *in situ*, and specimens of these are exhibited. From a consideration of these casts, and a comparison with the original sections of the new rails, it was found that metal was extruded both on the inner and outer sides of the rail head, and that in many places the outer side of the rail head was much worn by the vehicular traffic.

Records of Corrugation.—Two methods were devised for obtaining graphical records of the pitch and shape of the corrugations in plan.

In the first method a strip of thin tough paper was laid along the rail tread and drawn tight, it was then rubbed on its upper surface with a wooden rubber coated with blacklead, in the manner described in Experiment No 9 (see page 567).

In the second method a length of rail was coated with blacklead and polished bright, the paper strip was laid along this prepared surface, and the upper surface of the strip was rubbed longitudinally with a smooth clean block of wood.

The result obtained was the same as in the first case, except that the record was formed on the underside of the paper as it lay upon the rail, and therefore was not visible during the process of rubbing; for this reason the first method is to be preferred.

Preparatory to taking a record, the rail head was first carefully cleaned by means of a metal scraper, followed by a stiff wire brush, and was finally polished with a dry cloth.

Graphite records were obtained in this way from a large number of typical portions of electric tramway tracks, from main line steam tracks, and from the running rails and conductor rails (3rd rails) of electric railways (see Figs. 12 to 16).

In making these rubbings care must be taken to keep the paper strip stretched taut; if it is at all loose it is liable to cockle under the rubber, and to give rise to alternate light and dark patches of short pitch, which might be mistaken for corrugation.

Duplicate rubbings were taken to eliminate any error from the above cause, and although in some duplicate rubbings slight differences were found in the areas of the white patches or hollows, no variation was observed in the pitch or in the number of crests and hollows indicated on the records.

The rubbers employed were as a rule 2 in. wide, and of sufficient depth to be rigid, while in length they varied from 2 to 48 in

This variation in length was necessary to ensure the rubber block resting on the crests of at least two corrugations at one time. The short rubbers were used to record the corrugation of short pitch, which is found between higher crests of long pitch.

Wheel Contact Records.—Experience with the skidding cylinders used in the laboratory led to the devising of experiments on the track designed to record the variation in pressure between the wheels and the rails under service conditions.

For this purpose the rails were cleaned and coated evenly with printers' ink for a length rather less than that of the circumference of a standard wheel. At a point in advance of the coated rail in the direction of motion of the car a strip of absorbent paper was held in position on the tread of the rail. The distance between the coated rail and the paper was such that the tyre of the wheel in passing over the coated section took up the printers' ink at the points at which it made contact with the rail, and then as the wheel revolved further, printed off the impression formed on the tyre upon the paper slip.

Experience with this simple method of observation led to the substitution of graphite for printers' ink, and to the following modification of the procedure: A length of rail tread was coated with graphite, and polished bright, a paper strip was placed over this length, which was pressed upon the blackleaded rail surface by the wheel in its passage over it.

Fig. 17 shows some of the records obtained in this way; the variation in pressure between the wheel and the rail may be clearly seen from the variation in density in the graphite print. The white areas in the record mark the points at which there was no pressure between the wheel and the rail.

In taking a record a paper strip about 4 in. wide was pinned lengthwise along one edge of a thin wood board, so that the paper projected about 3 in. beyond the edge of the board throughout its length. The projecting portion of the paper was laid over the tread of the rail with its outer edge coincident with the gauge edge of the rail. A couple of short handles were fixed to the board, so that the operator was clear of the moving car. With a little practice it was found quite easy to obtain a record from the leading wheel of a car by pulling back the board before the second wheel reached the paper.

Occurrence of Corrugation.—In general, corrugation appears on the running rails of cable, steam, and electric traction systems. We have found pronounced corrugation on the rails of each of the five steam railway systems which we have examined in this country, but it is not present on steam or cable lines to nearly so serious an extent as it is on electric lines.

The positions in which visible corrugations occur on tramway track are well known and need not be specified.

The third rails of electric railways with sliding collector shoes are frequently extensively corrugated.

The trolley wire of tramway systems is often corrugated for short

lengths at bridge, bracket arm, or span supports, and for considerable lengths of the suspended wire between the supports.

Parts of machines making sliding or rolling contacts are frequently corrugated when there is some freedom of motion of one or other of the parts concerned at right angles to the surface rubbed.

A series of graphite rubbings of corrugations on collector rails and running rails of electric railways, on main line steam track, on trolley ears and trolley wire are shown in Fig. 12. The records from the City and South London Railway were kindly furnished by Mr. P. V. McMahon, to whom our thanks are due. The collector shoe employed is a rectangular casting, the lower surface of which is rounded to a large radius, and rests upon the collector rail. The shoe is pivoted on its rear edge to the locomotive frame and is pushed along the rail with its free edge leading. Recently a spring has been added to press upon the top surface of the shoe to improve the contact and reduce the sparking.

We have noticed corrugation on the collector rails of other railway systems and on the collector rings of alternators, and while no doubt the burning due to sparking when the contact is broken affects the result, we regard this as an effect rather than as the cause of the corrugation.

The following brief notes are appended dealing in detail with the rubbings illustrated in the figures :—

Fig. 12.—The graphite records for this figure were taken with a 12-in. wood rubber as follows :—

City and South London Railway.—Collector rails.

A. Running dead slow just before stop. Current about 5 amperes.
B. Running slow, accelerating, current about 280 amperes.
C. Running fast, coasting, current about 5 amperes.
D and E. Running rails.
F, G, and H. Running rails, main line steam track, Manchester.
I. Trolley wire, Manchester Corporation Tramways, between supports.
J. Trolley wire under the ear at a span support ; the support is flexible in a vertical plane.
K. Trolley wire under the ear at a support used in passing under bridges.

The ear is screwed to an insulating bolt fixed rigidly to the wooden troughing under the soffit of the bridge.

Corrugation in trolley wires frequently shows "pitting," due to arcing in the hollows ; this is due to the jumping of the trolley wheel on the crests.

Fig. 13.—Rubbings taken with a 12-in. rubber from the track of the Manchester Corporation Tramways, as follows :—

A. 40-ft. curve, outer rail.
B. 40-ft. curve, inner rail.

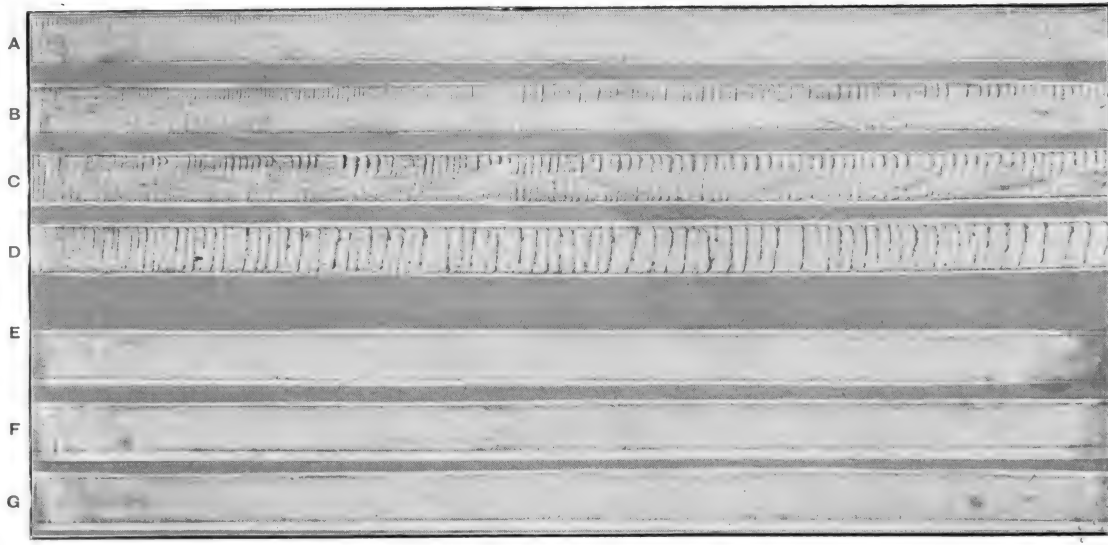


FIG. 9—Graphite Records from a Lead Bar rubbed with a Steel Cylinder.

A to **D,** unlubricated. (Experiment No. 9.) **E** to **G,** lubricated. (Experiment No. 10.)

Records taken at the following times from the commencement of the experiment :—

A	after 3 minutes.	**E**	after 3 minutes.
B	„ 13 „	**F**	„ 13 „
C	„ 23 „	**G**	„ 53 „
D	„ 53 „		

Direction of motion from left to right. Speed of rubbing cylinder, 160 ft. per minute.
(Scale, 5 mm. = 1 in.)

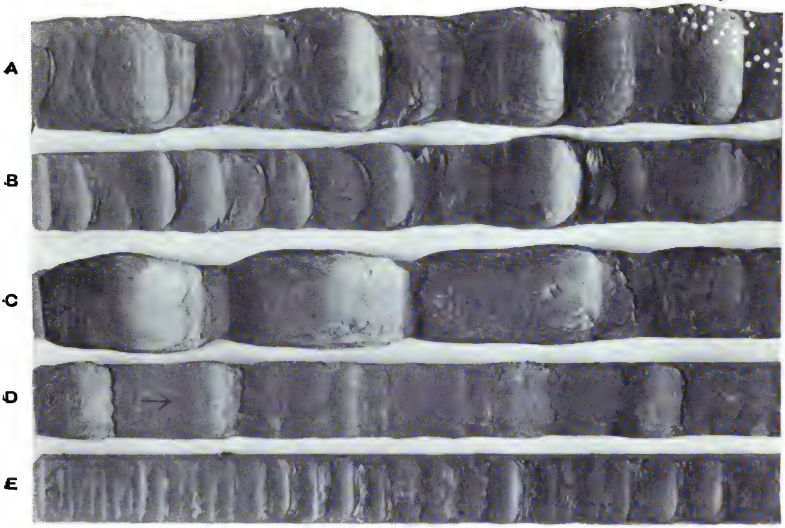


FIG. 10.—Effect of rubbing a Lead Bar with a Steel Cylinder 1 in. in Diameter under Various Conditions.

A Cylinder free to rotate. Short axis of connecting rod vertical. 100 hours (Experiment No. 11.)
B Cylinder fixed. Short axis of connecting rod vertical. 30 hours. (Experiment No. 11.)
C Cylinder fixed. Short axis of connecting rod horizontal. Artificial jump $\frac{1}{4}$ in. high at left-hand end of bar. 24 hours. (Experiment No. 13.)
D Cylinder fixed. Short axis of connecting rod horizontal, and weighted at centre. Cylinder trailed over bar. 18 hours. (Experiment No. 12.)
E Cylinder fixed. Connecting rod as in **D**. 1 hour.

Direction of motion, from left to right. Speed of rubbing cylinder, 160 ft. per minute. (Scale, 4 mm. = 1 in.)

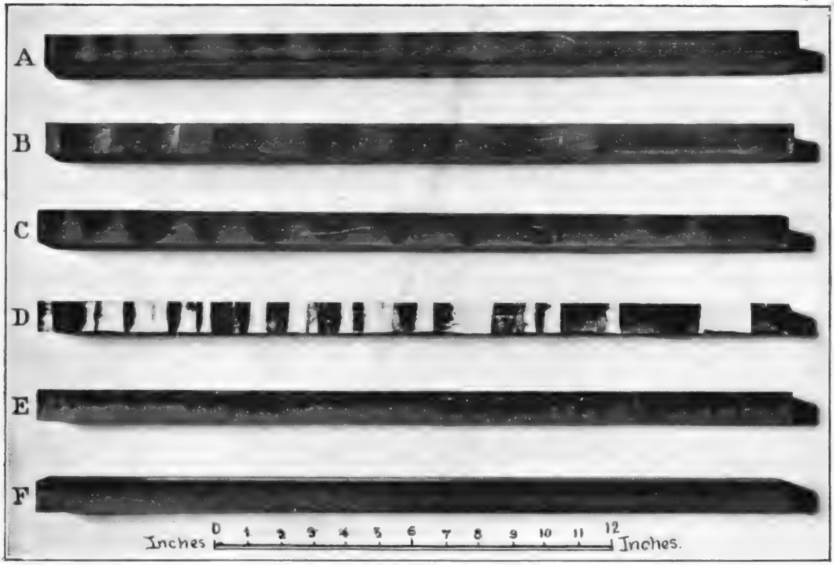


FIG. 11.

A Bar of yellow pine. Artificial jump. Initial stage. 20 minutes. (Experiment No. 15.)
B Bar as under (**A**). Final stage. 70 hours. (Expperiment No. 15.)
C Bar of yellow pine. No jump. 120 hours. (Experiment No. 16.)
D Bar of plaster of Paris. No jump. 5 minutes. (Experiment No. 18.)
E Lead bar, high angle of approach of connecting rod. 16 hours. (Experiment No. 19.)
F Lead bar, low angle of approach of connecting rod. 16 hours. (Experiment No. 19.)

In the above **A** to **D**, the hollows are shown black and the crests white. Throughout these experiments the short axis of the connecting rod was horizontal, and it was weighted at the centre, except for **C**, where it was vertical and unweighted.

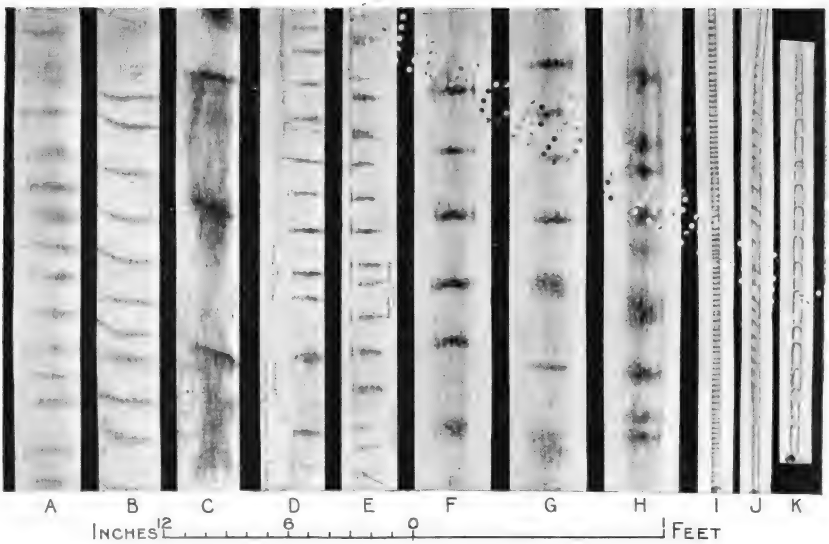


FIG. 12.

Direction of motion from bottom to top.
(For particulars see page 576.)

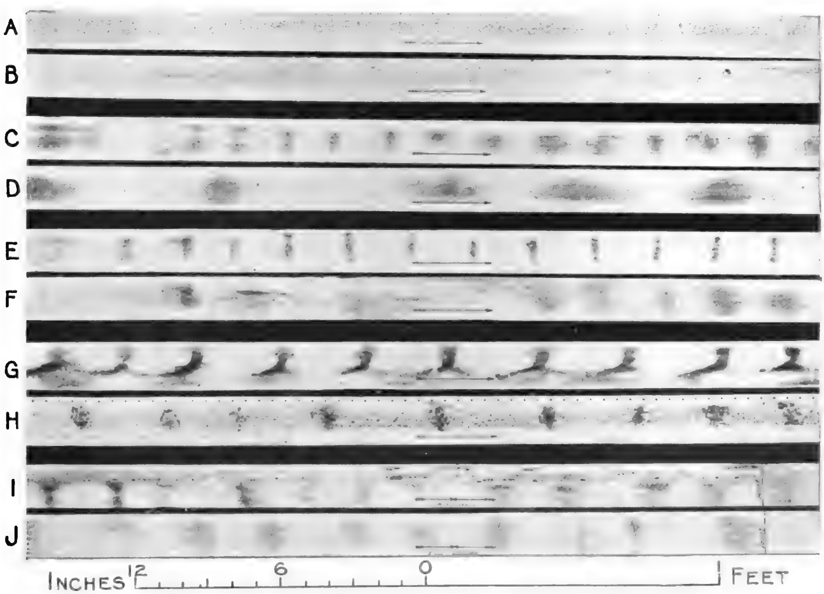


FIG. 13.—Graphite Records of Corrugation on Rails.

Direction of motion from left to right.
(For particulars see page 576.)

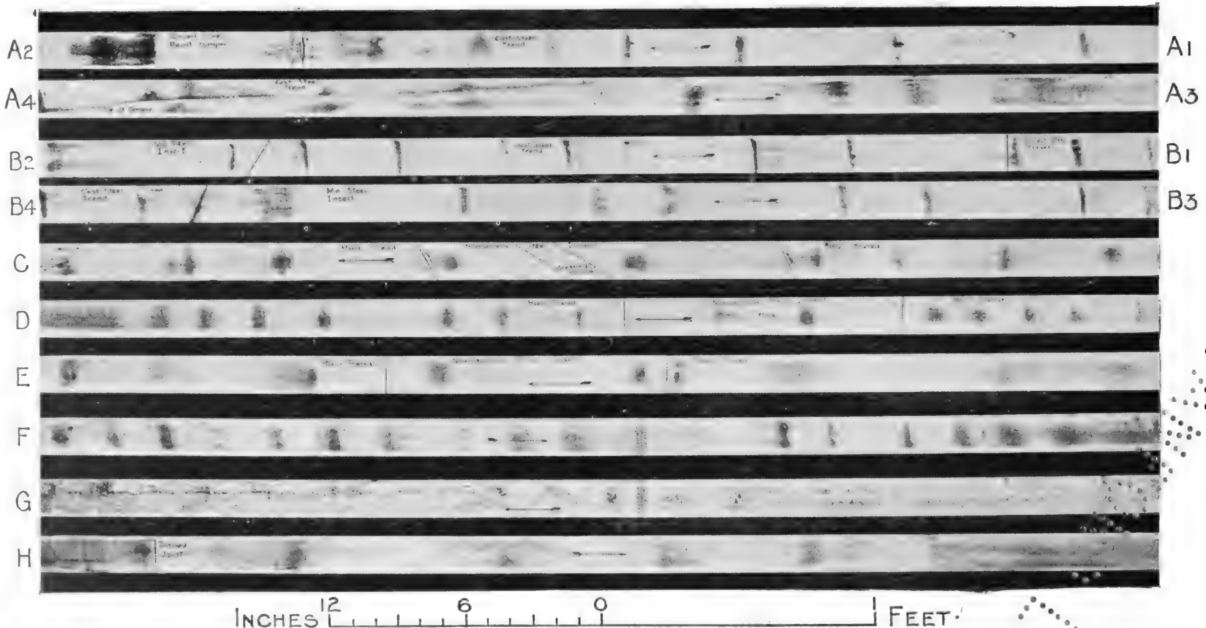


FIG. 14.—Graphite Records of Corrugation on Special Work.
(For particulars see page 577.)

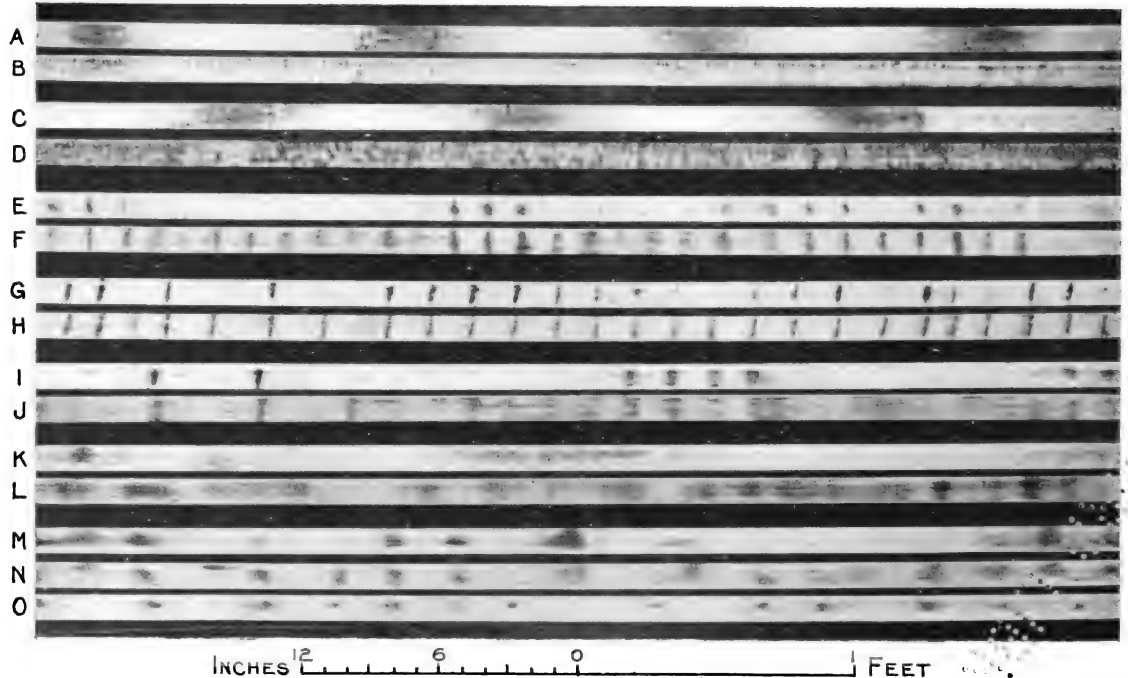


FIG. 15.—Graphite Records of Corrugation on Rails.

(For particulars see page 577. Scale 3 mm. = 1 in.)

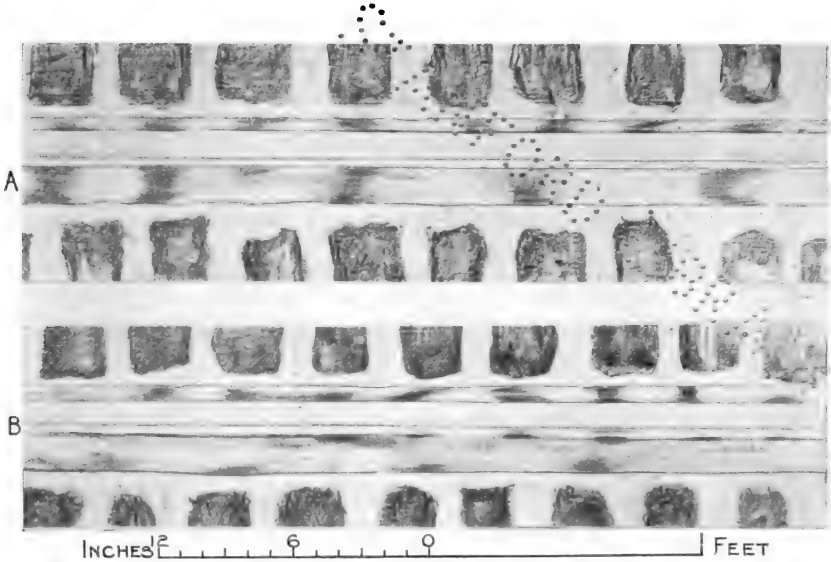


FIG. 16.—Corrugation due to Vehicular Traffic on Emergency Routes in Manchester.

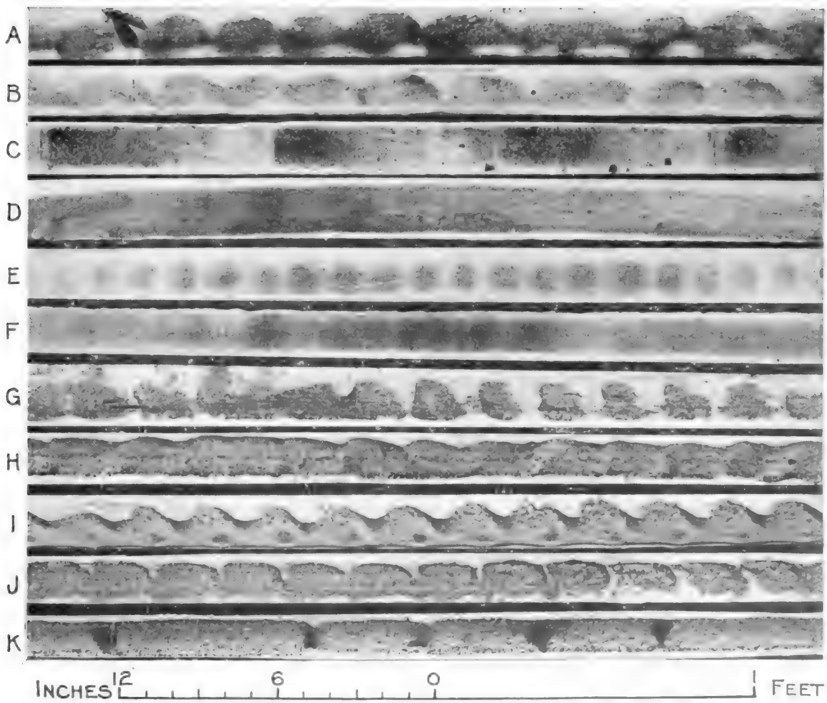


FIG. 17.—Wheel Contact Records.

(For particulars see page 578.)

The rails of sharp curves such as above are generally free from corrugation.

The wheels of cars passing round sharp curves are continually binding in the rail grooves, with the result that the car body, truck, and driving elements are locked together, and the vertical movements of the wheels are damped.

C. Outer rail of flat curve of very large radius.

D. Inner rail, opposite to C.

The radius of curvature is not uniform, the track following the curvature of the road, but in no place being less than 1,000 ft. The record D shows long corrugations on the inner rail.

E. Outer rail of flat curve.

F. Inner rail, opposite to E.

The record F shows both long and short corrugations on the inner rail.

G. Straight track, cars in one direction only as in usual practice. In this case the coned wheels run on a horizontal rail tread and bear at first on the gauge edge of the rail.

H. Similar rail on the same route with contact between wheels and rail at middle of rail tread.

I. Straight track, traffic in both directions equally. Gauge edge contact between wheels and rail.

J. Rail opposite to I, at the same place, showing approximate agreement between corrugations. Complete wheel contact.

Fig. 14.—Rubbings taken with a 12-in. wood rubber from special track fittings and joints on the Manchester Corporation Tramways.

A 1, A 2, A 3, A 4. Tread of cast steel point and forged point tongue.

B 1, B 2, B 3, B 4. Rolled steel rail, cast steel tread and manganese steel insert of mate point opposite to A and corresponding in position with it.

C. Arm and manganese steel insert of an iron bound crossing.

D. Machine-fitted manganese steel insert at a joint on the outer rail of a flat corrugated curve.

E. Similar insert on the corrugated inner rail of same curve.

F. Ordinary fish-plated joint.

G. Thermit-welded joint.

H. Dished joint.

Fig. 15.—Rubbings taken with rubbers of various sizes from rails of the Manchester Corporation Tramways as follows :—

New Rails before Laying :—

A. 36-in. rubber on tread of rail.

B. 12-in. rubber on tread at same place.

C. 36-in. rubber on under side of flange of rail at same place.

D. 12-in. rubber on under side of flange at same place.

The long rubbers show the corrugations due to the straightening process through which the rails pass after being rolled. The peaks on the tread of the rail are opposite the hollows on the flange, and the whole of the rail is sinuous. The pitch of such long corrugations is not constant and varies from 18 in. to 3 ft.

Visible Corrugations :—

E. Straight track, 36-in. rubber.
F. Same place as E, 12-in. rubber.
G. Outer rail of flat curve, 36-in. rubber.
H. Same place as G, 6-in. rubber.
I. Inner rail of curve opposite G, 36-in. rubber.
J. Same place as I, 6-in. rubber.

The records show the small corrugations appearing between the long-pitch waves.

Invisible Corrugations :—

K. 36-in. rubber.
L. 12-in. rubber.

The records are typical of those obtained from straight or curved track without visible corrugation whether in the streets or car sheds.

Vehicular Corrugation :—

M. 36-in. rubber on rail tread.
N. 12-in. rubber at same place as M.
O. 12-in. rubber on check top at same place as M.

The records shown are from a track not used by cars, but traversed by exceptionally heavy vehicular traffic. The hollows agree very closely with the joints of the stone sets surrounding the rails.

Fig. 16.—Rubbings of rails and surrounding stone sets from tracks not used for car services but traversed by heavy vehicular traffic between warehouses and stations.

A. Portland Street, Manchester, 12-in. rubber.
B. John Dalton Street, Manchester, 12-in. rubber.

The positions of crests and hollows are clearly shown in relation to the surrounding stone sets. In some cases the check of the rail is worn away at the set joints by the action of passing wheels of vehicles or by corrosion due to the collection of water at these points.

Fig. 17.—Wheel prints obtained from rolling stock and track of the Manchester Corporation Tramways, as follows :—

Graphite Wheel Prints :—

A. Outer rail of flat curve—high speeds.
B. Outer rail of flat curve—low speeds.
C. Inner rail of flat curve—high speeds.
D. Outer rail of a 40-ft. curve—all speeds give similar results,

E. Invisible corrugation—very high speed—straight track.
F. Same place as E—low speeds.

Similar records may be obtained from either front or rear wheels of cars whether driving or coasting. The variation of the wheel pressure on the rail is indicated by the variation in shade in the print, dark shades indicating higher pressure than light shades. Much variation is found in the records obtained at any given place from different cars and wheels owing to the variable wear of the wheel tyres, but this applies more to the area of contact than to the relative shades at different parts of the records.

Paint Records :—

G. Straight corrugated rail—very high speed.
H. Straight corrugated rail—low speed.
I. Outer rail of flat curve—high speed.
J. Outer rail of flat curve—low speed.
K. Inner rail of flat curve—high speed.

The jumping effect is shown by the failure of the wheels to take up paint at parts where wheel and rail are not in contact.

Great difficulty was experienced in obtaining records from low radius curves owing to the tendency of the wheels to drag the paper strips under the car.

VI. Deductions and Conclusions

A. *Laboratory Experiments.*

Formation of Corrugation.—A consideration of the experiments detailed under Section III. appears to show that the corrugation is initiated by the action of one or more of the following forces :—

(*a*) Jumping of the moving system on its passage over minute irregularities of the surface, or over an obstacle of some magnitude, when the critical speed is exceeded.
(*b*) Abrasion and displacement of the surface due to the difference between the static and dynamic coefficients of friction of the surfaces in contact.
(*c*) The longitudinal vibrations of the moving system.
(*d*) The transverse vibrations of the moving system.

In the case of a metal like lead the surface material is easily pushed forward, and the principal factor in initiating the corrugation would appear to be the abrasion of the surface and the progressive longitudinal displacement of metal, due to the great difference existing between the static and the dynamic coefficients of friction. This view is supported by the effect of lubrication (Experiment No. 10), the effect of a revolving cylinder in place of a fixed one (Experiment No. 11), the

effect of additional weight on the rubbing cylinder (Experiment No. 9), the fact that considerable alteration in the material and dimensions of the connecting rod does not materially affect the pitch of the corrugation in the initial stages (Experiment No. 21). The longitudinal vibrations of the connecting rod probably influence the corrugation in its initial stages, and assist in its formation, since they introduce a rhythmic to-and-fro movement of the cylinder which accentuates or reduces the effects due to friction, and possibly introduce a greater element of regularity in the results than would otherwise be present.

The effect of the transverse vibrations of the connecting rod may be noted in the earlier stages of corrugation on lead bars by the accentuation of the corrugation at intervals along the bar corresponding approximately to the period and amplitude of the vibration.

It is with a material such as wood, which does not lend itself to longitudinal displacements, that the effect of the transverse vibrations is most apparent. In this case the hollows of the corrugations are beaten out within limits set by the phase of the vibration acting on the vertical velocity of the rubbing cylinder, the crests being left at the original surface level—Experiment No. 11 (C).

Growth and Spread of Corrugation.—The main factor influencing the growth and also the spread of the corrugation is the hammering due to the jumping of the rubbing cylinder; in general the other factors may be regarded as being subordinate to this, and as affecting the form of the corrugation produced, and its degree of regularity.

B. *Corrugation under Service Conditions.*

The authors distinguish two classes of corrugation on the tramway track which they term "visible" and "invisible" respectively, according as the corrugations are visible to the naked eye or not. The presence of the invisible corrugation may be determined by means of graphite rubbings.

Invisible Corrugation.—The outstanding facts with regard to "invisible" corrugation as disclosed by the observations and experiments on steam and electric traction tracks are as follows :—

(*a*) "Invisible" crests and hollows of long pitch exist on new and unused rails owing to the methods employed by the manufacturers in straightening the rails (see Fig. 15A). These crests and hollows persist in the rails when laid as track.

(*b*) "Invisible" corrugation is found on the tread and the top of the check of rails laid in the roadway which are subjected almost exclusively to the action of heavy vehicular street traffic, the hollows between the long-pitch crests due to the straightening of the rails being filled with corrugations, the pitch of which is short and irregular and appears to be determined by the low points of the granite sets surrounding the rails (see Fig. 16).

(*c*) On rails laid in the car sheds which are subjected only to tramway traffic, the hollows between the crests of long pitch due to the straightening of the rails are filled with "invisible" corrugation of shorter pitch (see Fig. 15).

(*d*) "Invisible" corrugation similar to that described under (*c*) is to be found on the greater part of the Manchester system, and presumably on other systems also. In contradistinction to (*a*) it is found on tracks where the vehicular traffic is small, and where wood blocks are employed in place of granite sets next to the rails, as well as on the ordinary routes.

It appears probable that the formation of "invisible" corrugation referred to under (*c*) and (*d*) is due to a combination of forces similar to those present in the formation of the long-pitch corrugation in the cases of the lead bar and the wood bar with artificial obstacles introduced at their leading ends to cause jumping (see Experiments Nos. 13 and 15). In the case of "invisible" corrugation on the track, the obstacles would be provided by the long-pitch crests due to the straightening of the rails. The passage of the cars over these crests at the requisite speed would cause the wheels to jump and set up oscillations in the spring system of the car and in the truck body which would beat out the hollows of the corrugations, leaving the crests at or about the original rail level.

It seems probable that under normal conditions the specific pressure on the area of contact between the wheel and the rail and the amount of skid present on the wheels are not sufficiently high to allow of the progressive longitudinal displacement of the metal of the rail tread, but that the necessary power to beat out the hollows is furnished by the jumping of the wheel and axle with its non-spring borne load.

An alternative view is that the invisible corrugation referred to under (*c*) and (*d*) is formed by slow progressive longitudinal displacement of the metal due to the presence of a small amount of skid or slip of the wheels (see Experiments Nos. 8 and 20), the jumping action being very slight.

The matter might possibly be settled by putting under observation lengths of new rails from which the long-pitch crests due to straightening had been thoroughly removed.

A marked characteristic of "invisible" corrugation of short pitch is that it develops first on the top of the rail tread and not on the gauge edge, and the resulting crests have a larger area than those of the visible corrugation, and are more nearly at right angles to the long axis of the rails than are the latter. The boundaries of the crests are diffuse, and not definite as with visible corrugation.

Invisible corrugation does not appear to give rise to annoyance or trouble in practice to any extent; it increases very slowly, and may even reach a condition of equilibrium with respect to the general wear of the rail.

Visible Corrugation.—The main facts relating to "visible" corrugation are well known. The following additional facts have to be considered:—

(*a*) "Visible" corrugation is much more pronounced in character than "invisible" corrugation: the amplitude is greater, the area of the crests less, the pitch is perhaps slightly shorter and more regular, and in some cases the crests are higher than the general rail surface. The boundaries of the crests are definite.

(*b*) The inner rails of flat curves are generally less strongly corrugated than the outer rails, and the pitch in many cases is longer than that on the outer rails, but in some cases the pitch on both rails is equal, and the crests and hollows occupy corresponding positions on the two rails.

(*c*) The angle which the crests make with the long axis of the rail varies, being smallest when the corrugation is near the gauge edge; but as it extends across the tread of the rail, the angle increases, and approaches 90°.

"Visible" corrugation on the running track appears to be due to a combination of forces similar to those operating in the formation of corrugation on the lead bars (Experiments Nos. 9 and 11), in which progressive longitudinal displacement of the metal is brought about by the joint action of the forces concerned.

E. L. Hancock* experimenting on the areas of contact between wheels and rails, found with new cast-iron wheels weighing with their axles 1,800 lbs. and loaded to 2,200 lbs., that the area of contact was a minimum when the flange of the wheel was against the rail head, increasing for a normal position of the wheels, and reaching a maximum when the flange of the wheel in question was away from the rail head, and the flange of its mate wheel was against the gauge edge of the rail proper to it.

We see therefore that the specific pressure on the area of contact will be a maximum when the flange of a given wheel is against the rail head, and that with coned wheels on a flat rail tread the bearing surface will be close to the gauge edge of the rail where, as pointed out by Beaumont,† the metal is not held *encastrée.* The result will be that the wheels of the car travelling on the outside rail of a curve will have the maximum value for the specific pressure on the area of contact, and the tendency to jump will be increased by the climbing action of the flange referred to in Section III., page 560.

With regard to corrugation on the inner rails of curves, it appears to the authors that where this agrees in pitch and position with that on the outer rails, it is a case of transference of the impulses derived from the outer rail to the inner rail by means of the axle. In

* *Engineering News*, vol. 63, p. 154, 1910.

† "The Origin and Production of Corrugation of Tramway Rails," *Engineering*, vol. 92, p. 330, 1911.

this connection it may be observed that although the wheels on the outer rails frequently break contact with the rails when "jumping," we have not yet observed this to be the case with the inside wheels, the results showing variation in pressure on the contact only. As already stated, the presence or absence of continuity of contact between the wheel and rail profoundly modifies the character of the corrugation produced and its rate of growth.

Visible Corrugation on the Straight.—The characteristics of this corrugation are precisely the same as those of the visible corrugation on the outer rails of flat curves.

Our conclusions with regard to visible corrugation on the straight are as follows :—

(*a*) The visible corrugation is probably an augmentation of the invisible corrugation of short pitch present at almost all parts of the track.

(*b*) This augmentation may be due to variation in the specific pressure on the contact area between wheels and rail due to the position of the wheel flange relative to the rail.

(*c*) The position of the flange in the groove will vary with the following conditions :—

1. A constant contact of the flange of one wheel with the check or gauge edge may be caused by unequal diameters of the wheels. Owing to the prevalence of curves in one direction on a given route, and the use of particular cars on given routes, it is not infrequent to find the wheel diameters on one side of a car persistently greater or less than those on the other side.
2. An intermittent contact of the flange of one wheel with the check or gauge edge may be caused by differences between the coefficient of friction of the two rails. The wheel on which the friction is greatest will tend to lead and will throw the flange of its mate wheel against the gauge edge of the rail ; this will increase the friction on the mate wheel, which will then lead, and these alternations in lead will continue possibly with high frequency.

   In the event of the tyre or groove wear allowing the flange of either wheel to come in contact with the check the above-mentioned alternations will be set up and corrugation of the check may result.

(*d*) The flange action referred to under (*c*) may set up skid and a tendency in the wheel to climb the rail, thus giving rise to corrugation.

Conclusion.—The authors have purposely refrained from any suggestions as to possible measures for the cure or amelioration of corrugation, believing as they do that the first real step in the cure of a disease is its correct diagnosis. They trust that their observations and experiments may be found to contribute in some small measure to this end, and are hopeful that further *experiments* on the tramway track, together with a careful comparative study of the conditions obtaining on steam lines and tramway tracks, will yield a serviceable remedy.

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VII. APPENDIX.

Mathematical Considerations of Oscillations.

John Prescott, M.A.

The uniformity in the pitch of the corrugations on tram rails, as well as in those produced in the early stages of Professor Schwartz's experiments, suggests very forcibly that elastic vibrations of some kind, that is, vibrations of constant period, are the first cause of those corrugations. In this appendix are given the periods of the fundamental modes of vibration of the rod used in the laboratory experiments described in the preceding paper. It is useful to know the pitch of the waves which these vibrations would produce if the knowledge only proves to us that they are not the cause of the observed corrugations; for, considering the complexity of the problem and the number of plausible theories on the subject, it is only by a process of elimination that the true cause can be found.

The straight connecting rod R (Fig. 8) can execute transverse oscillations of exactly the same type as those of a fiddle-string. Supposing the rubbing end always remains in contact with the bar which is being rubbed these oscillations will cause a variation in the pressure on the bar, the maximum occurring once in a complete oscillation. The rod can also execute longitudinal oscillations like those of a spiral spring, and these, too, could cause a wave on the bar which is being rubbed.

Besides the two oscillations mentioned there is still another type possible, and considering the fact that the rubbing cylinder was attached on one side of the rod, these oscillations were very likely to be present. I refer to the torsional oscillations of the rod. The end of the rod twists backwards and forwards in the same manner as a disc at the end of a wire.

I will now give the periods of these oscillations and the pitches of the corresponding waves on the rubbed surface.

The following quantities refer to the connecting rod :—

l = length = 6 ft.
b = breadth = $1\frac{9}{16}$ in.
d = depth = $\frac{1}{4}$ in.
ρ = density = 7·7 grammes per cubic centimetre.
E = Young's modulus = $2 \times 10^9 \times 981$ dynes per square centimetre.

When the breadth b is horizontal the period of the fundamental transverse oscillation is—

$$t_1 = \frac{2\,l^2}{\pi}\sqrt{\frac{12\,\rho}{d^2\,\mathrm{E}}}$$

$$= \frac{4\sqrt{3}\,l^2}{\pi\,d}\sqrt{\frac{\rho}{\mathrm{E}}}.$$

When the rod was in this position the ends were twisted for the purpose of forming connections so that d was horizontal for about $4\frac{1}{2}$ in. from each end. So the rod was stiffened at the ends by this arrangement, and there will be very little error in subtracting this 9 in. from the length. Then, expressing lengths in centimetres—

$$t_1 = \frac{4\sqrt{3} \times 63^2 \times 30{\cdot}5}{\pi \times \frac{1}{4}}\sqrt{\frac{7{\cdot}7}{2 \times 10^9 \times 981}}$$

$$= 0{\cdot}176 \text{ second.}$$

When the dimension d is horizontal the period of the transverse oscillation is—

$$t_2 = \frac{2\,l^2}{\pi\,b}\sqrt{\frac{12\,\rho}{\mathrm{E}}}$$

$$= 0{\cdot}0368 \text{ second.}$$

The period of the fundamental longitudinal oscillations is—

$$t_3 = 4\,l\sqrt{\frac{\rho}{\mathrm{E}}}$$

$$= 0{\cdot}00145 \text{ second.}$$

If n denotes the rigidity modulus of the bar, the period of the torsional oscillations is—

$$t_4 = 4l\sqrt{\frac{\rho}{n}}$$

$$= 0{\cdot}00231 \text{ second,}$$

if we take $n = 785 \times 10^6$ grammes per square centimetre, the value for wrought iron.

When the crank was making 31 revs. per minute, as was the case for the earlier experiments, the velocity of the rubbing cylinder varied along the bar from 33 to 55 in. per second. The pitch of the waves which any of the preceding oscillations will produce is obtained by multiplying the velocity of the rubber by the period of the oscillation.

For the first transverse oscillation, the pitch varies from $33\,t$ to $55\,t$ in.—that is, from 5·8 to 9·7 in.

For the second transverse oscillation the pitch varies from 1·21 to 2·02 in.

For the longitudinal oscillations the pitch varies from 0·048 to 0·080 in.

For the torsional oscillations the pitch varies from 0·076 to 0·127 in.

When the 5-lb. weight was attached to the middle of the connecting rod the conditions were favourable for producing the transverse vibrations with the middle of the rod as a node, the two halves of the rod being in opposite phase. The period in this case is $\frac{1}{2}\,t$, and the pitch of the corresponding waves would vary from 2·9 to 4·8 in.

The quantities ρ and E for the wooden connecting rod are less reliable than for iron. The average values of these quantities for red pine, according to Rankine, are 35 lbs. per cubic foot and 16×10^5 lbs. per square inch, and these give 0·002 as the period of the longitudinal oscillations. In the experiments where the wooden rods were used the crank was making 13 revs. per minute instead of 31 as formerly. Also, on account of the different direction of rotation of the crank the velocities of the rubber are differently related to the velocity of the crank. From rough calculations I find that the velocity is a maximum near the middle of the stroke, and its magnitude there is about 21 in. per second. With this velocity the pitch of the waves due to longitudinal oscillations of the wooden rod would be about 0·042 in. When a rod of half the length was used the period of the vibration was halved, and if the velocity were the same the pitch would be halved. But the maximum velocity is rather greater in this case, so the pitch should be rather greater than half.

The Vertical Oscillations of a Brill 4-wheeled Single Truck.—The wheels are assumed to remain in contact with the rails while the truck and the

car body oscillate above it. The truck is supported by one set of springs and the total force required to compress all the 8 springs by 1 in. is 44,000 lbs. The car body is supported by 12 springs, which are attached to the truck. The force required to compress these by 1 in. is 14,800 lbs. The forces required to compress the two sets of springs are 528,000 lbs. and 178,000 lbs. per foot.

Let w_1, w_2 denote the weights of the truck and car body respectively. These are given (allowing for the weight of the motor) as 6,150 lbs. and 12,000 respectively. Let x_1, x_2 denote the extensions of the springs supporting w_1 and w_2. Then the vertical displacement of w_2 is $(x_1 + x_2)$, and the forces acting on w_1 are the forces of the springs above it and the springs below.

The equations of motion of the two bodies are—

$$\frac{w_1}{g}\frac{d^2 x_1}{d t^2} = 178{,}000\, x_2 - 528{,}000\, x_1,$$

$$\frac{w_2}{g}\frac{d^2 x_2}{d t^2} = -178{,}000\, x_2.$$

After putting in the values of w_1 and w_2 it will be found that—

$$x_1 = \mathrm{A} \sin \frac{2\pi t}{0{\cdot}102},$$

and—

$$x = -1{\cdot}14\, \mathrm{A} \sin \frac{2\pi t}{0{\cdot}102}$$

satisfy the equations of motion, A being any constant. These can be verified by substitution. The period of these oscillations is 0·102 of a second, and if the car is running at 15 miles an hour (22 ft. per second) the pitch of the waves due to them is about 27 in. It will be seen from the results that the truck and the car body are in exactly opposite phase.

Another pair of solutions which make the truck and the car in exactly the same phase are—

$$x_1 = \mathrm{A} \sin \frac{2\pi t}{0{\cdot}338},$$

and—

$$x_2 = 2{\cdot}6\, \mathrm{A} \sin \frac{2\pi t}{0{\cdot}338}.$$

The period in this case is 0·338 of a second, and the pitch of the waves is about 89 in.

These are the only regular vertical oscillations due to the spring system, and they are much too long to account for the well-known corrugations of 2 or 3 in. pitch on tram rails.

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DISCUSSION.

Professor E. W. MARCHANT: There is one point I should like to mention which has been discussed, I believe, in the first instance by Mr. Chase, and that is, as to how far corrugation is caused by the flexibility of the wheels and axles. One can imagine a pair of wheels going along a track and one of the wheels tending to rise on to the rail tread; one can suppose that the inertia of the car is tending to make the wheel, or rather the car, move in the direction in which this wheel is going (this sideway action of the car may, of course, be started in many ways; if the driving wheels are of slightly different diameters, for example, a sideway motion will be produced); the car moves in this direction, but the wheel is prevented from mounting the tread by the flange, and the edges of the two wheels are pressed together—that is, the axle and the two wheels form an H-shaped beam in which pressure is applied across the lower limbs of the H. Now, as soon as the force due to this squeezing action becomes great enough, the wheel that is not tending to rise on the rails slips back, and skids on the rail, and this process may, of course, be repeated, thus giving rise to corrugation. I mention this as a possible cause of corrugation. If the period of vibration due to the wheels and the axle combined were worked out, it would be possible to get some idea as to how far it was in accordance with the pitch of the corrugations that have actually been observed. As far as observation goes, corrugation appears to be due mainly to driving wheels. The corrugation that is got with steam trains is not so large as with electric trams, because the number of driving wheels going over the track in comparison with the trailers is very much **Professor Marchant.**

Professor Marchant.

smaller. The effect that has been described is more likely to occur with driving wheels, and hence is worth considering. It might be got rid of by making the wheels and axles even stiffer than they are at present.

Mr. Prescott.

Mr. J. PRESCOTT: As to whether corrugations are caused by vibrations or not, I cannot say that I have come to any very definite conclusion. In Professor Schwartz's experiments there were some short-pitched corrugations, something like $\frac{1}{10}$ in. long, which were always visible at the beginning, and these, I feel fairly sure, are due to some elastic vibration. But the calculations given in the paper show that they might possibly be due either to the longitudinal vibrations of the rod or to the torsional vibrations. These latter were certain to be present because the rubbing cylinder was attached on one side of the connecting rod. I could not decide for certain which of these two oscillations was the cause of the corrugations, but the torsional oscillations seem the most probable cause. I cannot say whether the longer-pitched corrugations in these experiments were due to oscillations or not, but I am inclined to think oscillations are among the causes. The calculations concerning the vibrations of a Brill truck show that the oscillations due to the spring system could not produce the well-known corrugations of 2 in. or 3 in. pitch on tram rails. But this does not mean that oscillations are not the cause, for there are many parts of a truck which can cause oscillations besides the springs. It would need an accurate knowledge of the rigidity of the parts of a truck to enable it to be decided whether oscillations of the right period are possible. Referring to Mr. Cunliffe's remark that corrugations were imprinted on their strips of paper when a car passed over at high speeds, while no corrugations were found at low speeds, it is quite possible that what they take for corrugations are merely records of the vibrations of the wheel in that particular passage. If the same marks cannot be discerned for the slow passage, then this explanation seems probable.

Mr. Harrop.

Mr. D. HARROP: I was associated with the authors in their experimental work on the subject, and can therefore appreciate the difficulties and more or less hazardous nature of research conducted under service conditions. The dodging of almost every conceivable form of vehicular traffic has become an art; whilst the depressing fact had to be faced that the various theories advanced were upset with most monotonous frequency, increasing the complexity of the problem enormously. Under these circumstances it is most natural that those assisting in the investigation should be more or less imbued with the theories and opinions of the authors. At the same time it has struck me that hardly sufficient attention has been paid by the numerous investigators of this elusive subject to the local conditions in the nature of the substructure of the permanent way foundations. Whilst not, perhaps, a fundamental, it is quite possibly amongst the many contributory causes of corrugation. For example: Take a length of track ¼ mile in length to all appearances perfectly straight and level. For

the first 100 yards or so no corrugation might appear, and then appears a patch of badly corrugated rail, perhaps pair of rails on the same track, each showing similar corrugations to the other, or each showing corrugations totally unlike the other. The gauge is tried, and this appears to be quite normal, being neither tight nor slack ; the levels are taken and found to be quite correct ; in fact, outwardly no reason can be assigned for the appearance of corrugation on this particular length of rail or rails. Yet there must be some factors conducing to the production of slip or skid or flange action varying the contact pressure between wheel and rail at this particular point. On an ordinary route, conditions being fairly normal, slip or skid on a number of cars passing over the metals with reasonable frequency, would be thought to average out evenly over the whole route. Gauge, levels, and alignment being correct, the bedding of the track must be looked to. It must obviously be difficult to lay a considerable length of track on a continuous concrete bed, as is usual in tramway practice, perfectly flat, and in some cases packing has to be resorted to. This makes for varying degrees of rigidity in the track foundation, and would appear possibly to be one of the contributory factors to the appearance of corrugation. The corrugations or undulations, due to the straightening process in the rail manufacture, are interesting. And it would be still more interesting if, when new rails are laid in the street, a survey was made, and the "peaks" of these corrugations were marked and fixed relative to some permanent point in the roadway. This could be re-surveyed periodically, and the small corrugations fixed in relation to the original corrugations, and the movement, if any, of the original peaks noted. **Mr. Harrop.**

Mr. J. FRITH : One very valuable thing about the authors' paper is that it disproves almost every theory that has already been put forward about rail corrugation, that is to say, disproves it as being the only explanation. We are almost forced to conclude that wherever there is relative motion with friction, there is corrugation, and also some other cause tending to obliterate the corrugation. The causes tending to corrugation may be grouped under three general headings : (1) The fact that static friction is greater than dynamic, so that the motion tends to overrun the cause, then stop for a bit and then go forward, and so on ; (2) any vibration between the two pieces in contact set up possibly by quite outside causes will start corrugation, which will then continue and accentuate the vibration ; (3) if the pressure set up on the area of contact is sufficiently great to stress the material beyond its elastic limit, it will flow forward under that stress until the surrounding material prevents further displacements, when the wheel will jump and the process will begin anew. In practice it will generally be found that all three causes are operative in varying degrees. The causes tending to obliterate corrugation are not far to seek ; in tramway and railway working the action of the wheels, both driving and trailing, undoubtedly tends to roll the rails flat again. The fight against corrugation must obviously take the line of mini- **Mr. Frith.**

Mr. Frith. mising as far as possible the causes tending to corrugate, and secondly, making the conditions as favourable as possible to the removal of the defect if once set up.

Mr. Parrott. Mr. R. G. PARROTT: I believe I am correct in saying that such a thing as rail corrugation was unknown in the days of the horse trams, and that it is only since the introduction of high speeds that corrugation has appeared. It seems to me that there must be a critical relative speed between the wheel and rail at which corrugations begin to form rapidly, in a somewhat similar manner to the formation of corona on, say, a transmission line when the voltage reaches the critical value. I should therefore be glad if the authors would state if they have been able to arrive at any equation connecting the relative surface speed with the formation of corrugations, in which the pressure between wheel and rail and the diameter of the wheel are factors. It would be extremely interesting to know if the pitch of the corrugation would always remain constant under these varying conditions. With regard to the effect which the composition of the metal has in the formation or exaggeration of corrugations, I should like to ask the authors whether they do not consider that this is chiefly due to the friction between the wheel and rail. I suggest this because I have seen roller bearings which have been run for thousands of miles, on which there is no sign of corrugations on either roller or shaft. Perhaps the authors know of some case where corrugations have appeared in roller bearings. With reference to Fig. 2 of the paper, it will be noticed that the difference in percentage slip and the percentage skid between the curves A and C are not the same at any particular radius of curve. I should be glad if the authors would point out what this difference is due to. The authors do not state, in connection with the tests for slip and skid on curves, whether the tests were carried out with any super-elevation of the outer rail or not. If the track was laid level the results would be affected by flange friction. I have observed on a straight tramway track series of corrugations alternately on the left- and right-hand rail. Can this be shown to be mainly due to the swaying of the car body—possibly due to unequal strength of springs connecting the body of the car to the truck, or due to unequal pressure on the brake blocks when pulling up? Lastly, in connection with the corrugations on trolley wire, does the pitch of the corrugation bear any relation to the length of span? and are corrugations present on a catenary-suspended trolley wire?

Mr. Ellwood. Mr. C. F. ELLWOOD: On page 577, vi., the authors mention: "(*a*) Jumping of the moving system on its passage over minute regularities of the surface, or over an obstacle of some magnitude, when the critical speed is exceeded; (*b*) abrasion and displacement of the surface due to the difference between the static and dynamic coefficients of friction of the surfaces in contact," as two of the causes of corrugation. I have noticed on a length of the Manchester tramways a beautiful stretch of straight track, a series of longitudinal scratches as nearly as I can tell parallel to the rail edge.

These scratches or "abrasions" are due to either slip or skid, and are, to my mind, incipient corrugations. The scratches are 2 in. to 3 in. long, and in patches, and the authors say that corrugations appear in patches. The action of a jumping wheel when it alights is to produce "skid" or "slip," perhaps both. And the foregoing, I think, bears out the authors' contentions in (*a*) and (*b*). I have tried producing corrugations with sand, but without success. The marks on the rails which Mr. Prescott mentions may be seen on short-radius curves traversely across the track in a favourable light, but the wheel records that Mr. Cunliffe shows are corrugations. **Mr. Ellwood.**

Mr. W. Cramp: The corrugations shown to-night are apparently, to some extent, similar to those found in the work that has been done with fluids on sand. We know that a fluid such as water which has a very small viscosity, gives the closest approximation to pure rolling motion. We also know that if a trench of water be taken and the water be set in motion with sand at the bottom on which there is a little mound, this little mound is gradually repeated along the surface of the sand in the shape of smaller mounds, precisely like that figure which Professor Schwartz has put on the board. This is sufficient to account for the fact that initial lumps in the rail will produce a continuous corrugation. The most important deduction from the paper was mentioned by Mr. Frith, viz., that any single explanation hitherto put forward seems to fail in some particular, therefore the cause is probably complex, each suggestion being a partial truth. It is only a few months ago that Mr. Worby Beaumont gave a short paper on the subject before the British Association, in which he seemed to state definitely that he had not only found a cause, but *the* cause; and he told us what to do to get rid of it. He says in the conclusion of this paper that we must have lighter cars, larger wheels, harder rails, and moderate speeds. In other words, stop running the cars, build new ones, and run them slower. This is a sweeping conclusion, hardly warranted by the facts, and certainly not practicable. Speaking of small troubles, is it not true that in certain municipal tramways a special rubber is run over the rails at night to take out the corrugations? If that is the case, is it not possible to check one of the suggestions of this paper at once? I mean, can we not find out whether the corrugation set up is, in the first instance, due to the initial asymmetry of the rail? It would seem to be possible, before the rails are run over by carts and trams, to take out these initial lumps by rubbers, and then to note whether corrugation appears more slowly, in a different manner, or not at all. With regard to the question of flexibility mentioned by Mr. Worrall, I have read that rails with longitudinal sleepers show much more corrugation than rails with transverse sleepers. The track used by municipal tramways is, of course, notoriously rigid. It is not only bedded on concrete from end to end, but the rails are practically laid in one piece, being welded at the joints. If the transverse sleepers cause less corrugation, then it would seem also to follow that a flexible track is better than a rigid **Mr. Cramp.**

Mr. Cramp. track. If corrugations are set up by pushing over of metal or even by a hammering such as would be set up by oscillation of the car, then to me it seems that the rails when examined under the microscope at each hollow should appear harder and closer grained than at the crest. I would ask the authors, therefore, whether they have examined the different portions of the rail to see whether there is a difference in texture visible on fracture or under the microscope.

Mr. Davies. Mr. J. DAVIES (*communicated*): I have read with much interest the paper by Professor Schwartz and Mr. Cunliffe on the subject of corrugation of rails, and as Chief Engineer of the Hudson and Manhattan Railroad Company, have pleasure in reciting the experience of the Company with respect to this matter. The Hudson and Manhattan Railroad consists of tunnels between the Borough of Manhattan, City of New York, and the cities of Hoboken and Jersey City, in New Jersey. In a large measure this system consists of tube tunnels, as the entire road is below water-level, and, owing to franchise requirements, the route of these tunnels under the land portions coincides with the route of streets, and in consequence of this there is involved in the route, design, and construction of this system of tunnels a large percentage of curvature. This railroad is equipped and operated solely for rapid transit passenger service, and on one main line of the system in the State of New Jersey the tracks come up to the surface and connect with tracks of the Pennsylvania Railroad, over which trains of the Hudson and Manhattan Railroad are operated to Newark, N.J. In New York this system has two termini: *i.e.*, one in the down-town district of the city at Church Street, which is reached by two single-track tubes crossing the Hudson River between the Pennsylvania Railroad Station in Jersey City and the terminus in Church Street, New York City, between Fulton and Cortlandt Streets; the other terminus in the up-town district of New York City, reached by two single-track tubes crossing the Hudson River between Hoboken, N.J., and the foot of Morton Street, New York City, thence extended under Sixth Avenue northward to Thirty-third Street and Broadway.

All the car equipment operated on this railroad is of one class and type; that is to say, steel passenger cars 48¼ ft. coupled length. These cars are equipped with two four-wheel bogie trucks 33 ft. centre to centre, and each car is equipped with two motors each 160-H.P. General Electric No. 76 type. On some of the car equipment both motors are attached to one truck, and the wheels of these motor trucks are 34¼ in. in diameter, and the wheels of the trailer truck 30 in. in diameter. On the remainder of the car equipment one motor is attached to each truck, and on these cars the trucks are arranged with one pair of driving wheels 36 in. in diameter and one pair of trailer wheels 33 in. in diameter. All wheels are of the standard Master Car Builders' section. All trains are operated in multiple unit, and are equipped with the Sprague-General Electric multiple-unit control. Throughout the system the running rails are

Mr. Davies.

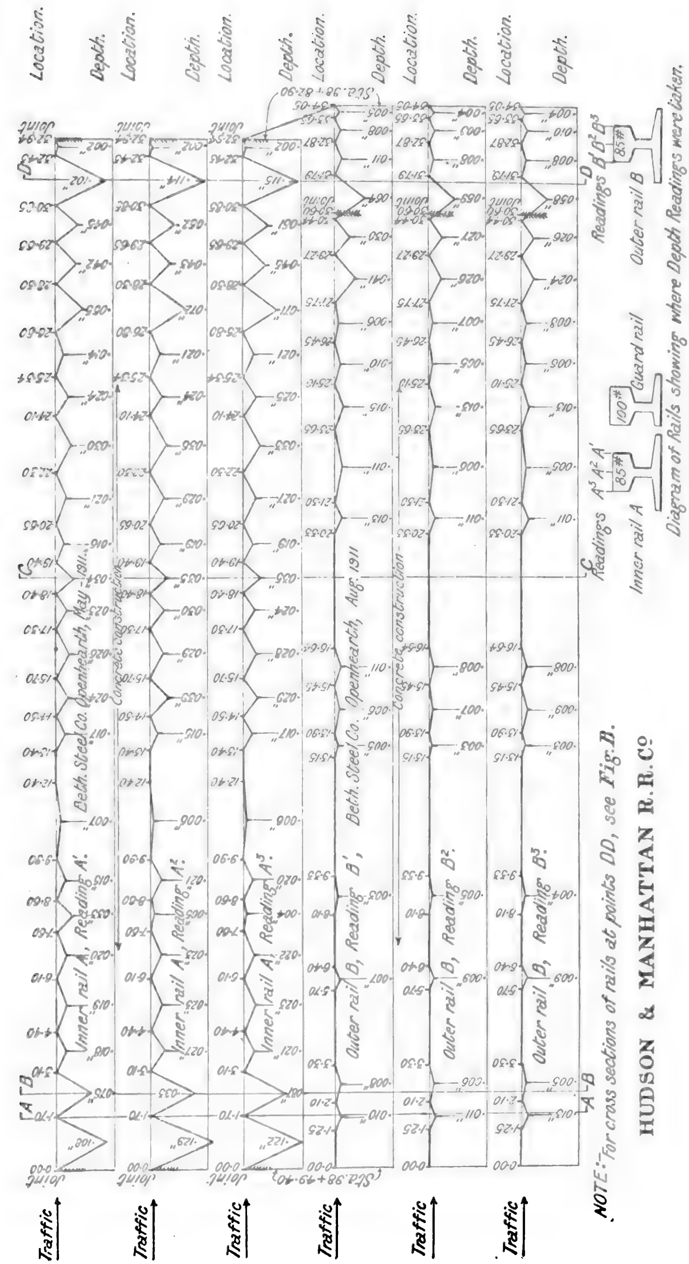


FIG. A.

Scales.

Hor.: 1 in. = 3 ft. Ver.: 5 in. = 1 in.

Mr. Davies. 85-lb. American Society of Civil Engineers' section, and in the original installation of the portion of the line between Hoboken and up-town New York rail manufactured by the Bessemer process was used, containing 0·55 to 0·65 carbon. In the later equipment of the down-town section between Hoboken, Jersey City, and down-town, New York, rails made by the basic open-hearth process were used having the following chemical composition:—

Carbon	0·75 to 0·90 per cent.
Phosphorus	0·03 per cent.
Silicon	not over 0·20 per cent.
Manganese	0·70 to 1·00 per cent.

Manganese rail—either cast or rolled—is used for the outside rail on curves of from 500 to 600 ft. radius. On all curves less than 200 ft. radius, both track rails are of similar manganese steel. Soon after trains were placed in operation corrugation of rails appeared on various portions of the track and steadily increased in number and depth of waves. The increased wear and tear on equipment and discomfort to passengers by car vibration, necessarily shortening the service of rails thus affected, had led to extended study of the phenomenon to determine the probable cause. Surveys of corrugations have been made to determine the length and depth of the waves, the extent of track affected, the alignment, grade super-elevation, gauge, foundation of track, location of rail splices, and influence of guard rail, and all these details have been carefully noted. It has been found on this system that the corrugation of rails is not by any means confined to track on curves, but extends in a great many instances to track on long stretches of tangent where curvature has no bearing whatsoever upon the resulting conditions. The Figs. A, B, C, and D show typical results of corrugation surveys on curve and on tangent track. Though no definite conclusions can be deduced from these data at the present time, the results of observations and surveys seem to indicate that combinations of the following conditions tend to produce corrugations, namely: (1) The concentrated weight of motors on car trucks and the small diameter of driving-wheels, particularly bearing in mind that all equipment operated is of identical type and operated, as before stated, under multiple-unit control. (2) The excessive number of wheels to which power is applied, as compared with railroad trains propelled by steam locomotives. (3) The application of power approximately at one end of car axle, due to the location of the gearing, aggravating the condition of torsion on the axles. (4) The sudden application of power, and, to a less extent, also the application of brakes. (5) Rail splices may be low and also may be too rigid, due to excessive tamping of ballast, or splice-plates may cause the rail to assume a stiffness at splices in excess of other points of the rail. (6) The bearing of car bodies on trucks may be too rigid, and there may

be other faults in truck design. (7) Very wide gauge on tangent track, permitting of the "nosing" of trains laterally, causing riding up on the cones of wheel-treads. (8) Improper setting of flangeway where guard rail is used on curves. (9) Improper gauge of outer rail with reference to the guard rail. (10) Improper super-elevation of curves. (11) Soft spots in rails and other defects due to manufacture. Several combinations of the conditions above enumerated tend to cause the car-wheels to climb the rail, and then when the wheels abruptly fall back to their normal position, indentations are produced on the rails, and these indentations in turn form obstructions to the wheels, thus producing a still further tendency toward climbing and causing a progressive series of indentations. Mr Davies.

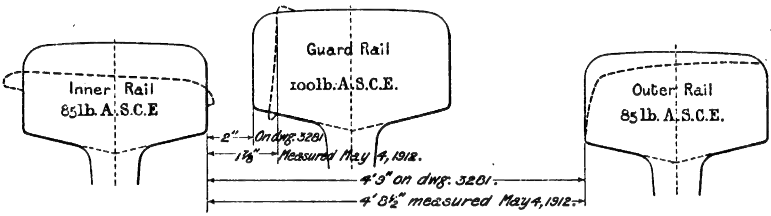


FIG. B.—Rail Sections showing Wear.

Kind of steel, Openhearth.	Kind of steel, Openhearth.	Kind of steel, Openhearth.
Superelevation, 3½ in. (measured).	Superelevation, 3½ in. (measured).	Superelevation, 3½ in. (measured).
Flangeway, 1⅞ in. (measured).	Flangeway, 1⅞ in. (measured).	Flangeway, 1⅞ in. (measured).
Months in use, 8·6.	Months in use, 5·5.	Months in use, 2·6.
Wear of head, 30·6 per cent.	Wear of head, 10·3 per cent.	Wear of head, 15·1 per cent.
Traffic factor, 1·06.	Traffic factor, 1·06.	Traffic factor, 1·06.
Corrected wear, 32·43 per cent.	Corrected wear, 10·92 per cent.	Corrected wear, 16·07 per cent.
Wear per month, 3·77 per cent.	Wear per month, 1·98 per cent.	Wear per month, 6·14 per cent.

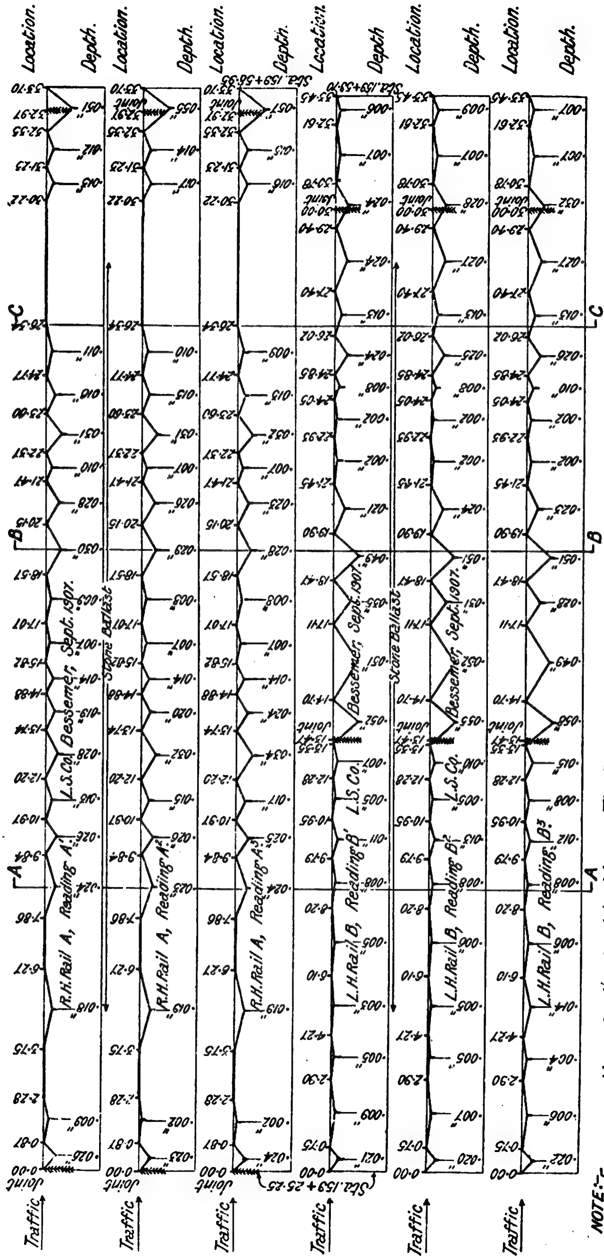
Tunnel, B. Curve, No., 28 Bx.
Traffic, Eastbound. Radius, 165·476 ft.
Grade, + 1·0265 per cent.

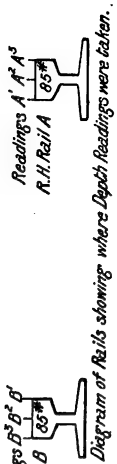
Note.—Sections facing in direction of normal traffic. Percentage wear of head equals area worn away divided by full area of head when new.

Note.—Section taken at point DD, as shown on Corrugation Drawing, Fig. A.

On the Hudson and Manhattan system it has appeared that the wave-form is caused by the slipping or sliding of the wheels as they fall back on the rail, thus ironing and grinding down the indentations into the form of waves, and we are of the opinion that the waves are not due so much to the piling-up of metals at intervals along the rail. In our experience there has appeared no evidence of any steady flow of metal in the direction of traffic, such as is indicated by the photographs which illustrate the authors' paper. Another possible contributing cause which has suggested itself as a result of our investigations relates to the construction of the wheel flange. The contour of the flanges (which conform to the standards of the Master Car Builders' Association) when applied to small-diameter driving-wheels, operated by motor drive on the axle, may possibly have a too gradual slope and

Mr. Davies.





NOTE:—For cross sections of rails at points AA, see Fig. D.

HUDSON & MANHATTAN R.R. Co.

FIG. C.

Scales.

Hor.: 1 in. = 3 ft. Ver.: 5 in. = 1 in.

too much coning of the tread to produce the most satisfactory results in the operation of a service such as that of the Hudson and Manhattan Railroad. This gradual slope of the face of the flange in contact with the rail increases the tendency of the wheel to climb in rounding curves as well as when "nosing" along tangents. It naturally is manifest that this condition reduces the area of contact, and when the climbing of the wheels on the rails reaches a point where the weight of the car overcomes the climbing effect, the wheels drop back to the rails with a noticeable slipping along the rail. This condition is very apparent from cross-sections we have taken of rails and car-wheel treads, and has been observed to be actually common in practice. It might be added that sections of rails used in electric Mr. Davies.

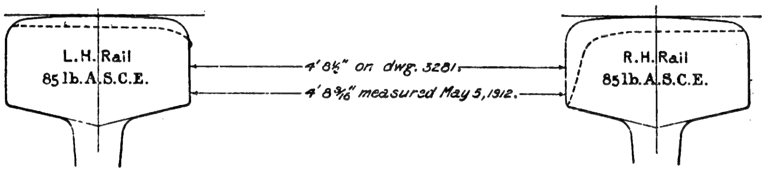


FIG. D.—Rail Sections showing Wear.

Kind of steel, Bessemer.
Superelevation, L.H. Rail $\frac{3}{8}$ in. (measured).
Flangeway, None.
Months in use, 50·3.
Wear of head, 9·6 per cent.
Traffic factor, 1·06.
Corrected wear, 10·18 per cent.
Wear per month, 0·2 per cent.

Tunnel, B.
Traffic, Eastbound.

Note.—Sections are shown facing in direction of normal traffic. Percentage wear of head equals area worn away divided by full area of head when new.

Kind of steel, Bessemer.
Superelevation, L.H. Rail $\frac{3}{8}$ in. (measured).
Flangeway, None.
Rail put in track, Feb. 25, 1908.
Section taken, May 5, 1912.
Months in use, 50·3.
Wear of head, 18·6 per cent.
Traffic factor, 1·06.
Corrected wear, 19·72 per cent.
Wear per month, 0·39 per cent.

Curve No., Tangent.
Grade, – 2·41 per cent.

Note.—Section taken at point AA, as shown on Corrugation Drawing, Fig. C.

transit service are heavier and have more depth in comparison to the loads supported than on steam railroads, thus providing a stiffer surface for the wheels to roll on, and in many cases this stiffness is augmented by a very close spacing of ties and a solid foundation. In consequence of this condition of the track, any blow from the wheels is more likely to produce indentation on the head of the rail than it would if the rail and road-bed were constructed with less rigidity. Assuming that the conditions briefly referred to above, with respect to car equipment and track, do tend to produce corrugation of rail, it is quite apparent that the remedy lies in a modified design of the running gear of the car equipment and closer attention to the maintenance of track and road-bed. The conclusions reached by Professor Schwartz and Mr. Cunliffe coincide to a large extent very closely with what we have found in practice, and the authors are to be congratulated on the careful and painstaking experiments.

Mr. Smith.

Mr. Roger T. Smith (*communicated*): On British railways the effect on the running rails of a change from steam working to electric working has generally resulted in more or less serious corrugation of the rails. In the present state of knowledge all the causes which go to produce corrugation as distinct from rail wear have not been separated, and for railways as opposed to tramways it is perhaps not necessary to separate them. There is a general agreement that one of the chief causes of both wear and corrugation is the sideway wobbling of a bogie truck. Steam locomotive engineers discovered long ago that raising the centre of gravity of the locomotive was one very important factor in preventing side wobbling. But the method adopted on practically all the electrically worked lines in this country is to hang the electric motors in the bogie trucks of passenger coaches and so lower the centre of gravity of the motor coaches to an undesirable extent. In contrast to English electrified lines, on the Continent and in America the nature of the traffic has in many places got beyond the suburban type, where the multiple-unit system of control is essential for satisfactory working. The use of the electric locomotive allows the benefit of high centre of gravity, and all designs of modern electric locomotives provide for it. A second cause of truck wobbling and hammering lies undoubtedly in the fact that in multiple-unit control rolling stock the electric motors are not spring-suspended from the wheel axles at all, and in the case of their second support are only in part spring-suspended by the attachment to the bogie truck. If complete spring suspension were provided for the motors, both this cause as well as the first cause mentioned of corrugation and undue wear of the rails would be removed, since complete spring suspension of the motors must result in raising them above their present level. This could only be done in a motor coach by sacrificing floor space used for standing or seating accommodation.

The third cause of truck wobbling is the comparative short wheel bases employed. In nearly every suburban electric railway in this country more or less trouble has been experienced with motor bogies, and in some cases they have had to be almost entirely reconstructed after frequent breakages. The question of the design of a motor bogie does not appear to have received sufficient attention from those responsible for the electrification of railways, and in many instances the experience gained by steam locomotive engineers has not been fully utilised, or if it has been utilised the steam engineers have not sufficiently understood the problem they had to solve. There ought to be no difficulty in making motor bogies with a 10 ft. or 10 ft. 6 in. wheel base for electric traction, and it is suggested that both corrugation and wear on electric railways could be largely reduced by a combination of these features—high centre of gravity, spring suspension of motors, and long wheel bases. Supposing that this had been done for multiple-unit rolling stock at the sacrifice of seating and standing room in the first two cases and by increased bogie weight in the third case, with a marked decrease in the wear of rails and

especially in corrugation as the result, the question which the management of any railway has to consider is, would it pay? Mr. Aspinall, speaking in his Presidential address before the Institution of Mechanical Engineers in 1909, suggested that it might be the more economical thing to wear out the rails and not to try to save them by expedients that might wear out more expensive machinery or decrease the earning capacity of the train. These questions can only be answered after careful investigation, but their statement will serve to show that the problem for the railway engineer and for the tramway engineer is not the same. The costs and inconvenience incidental to renewing tramway rails are far greater than for a railway, and it may well be that in the case of tramway traction prevention of corrugation may be so important as to lead to a modification in the present method of placing heavy motors without spring suspension or with only a partial spring suspension in such a position in short-wheel base trucks that the centre of gravity of the whole car is lowered. **Mr. Smith.**

Professor A. SCHWARTZ and Mr. R. G. CUNLIFFE (*communicated reply*): In considering the vibrations set up by car trucks periodic times other than those of the spring system must be considered. The side members of the truck frames may vibrate with frequencies greatly in excess of those of the various types of spring, and such vibrations may be superimposed on the slower spring vibrations. The presence of high-frequency vibration can often be felt by passengers, and we attribute such vibrating to the chattering action produced by skid of the wheels on the rails. The presence of imprints of corrugation on the paper strip with the passing of a car at high speed was not due to wheel vibration even where low speeds showed no sign of corrugation imprints on the paper strip. Graphite rubbings taken at the same part of the rail showed that corrugation was present on the rail and high speeds caused the wheels to jump, thus producing alternate light and dark patches on the paper strip employed for recording the wheel contacts; the jumping was absent with low speeds. **Professor Schwartz & Mr. Cunliffe.**

The stiffening of the wheels and axles suggested by Dr. Marchant has been carried out on several tramway systems without appreciable effect on the corrugation waves either as regards their pitch, depth, or the extent to which they are present.

The nature of the substructure of the track, referred to by Mr. Harrop, opens out a large subject; the conclusion arrived at by us is that increased rigidity of the track tends towards the production of corrugation chiefly by increasing the forces between wheels and rails due to the blows produced by jumping. Many cases of damage to substructure are produced by the passage of cars over corrugated rails, and the damaged substructure must be regarded as an effect rather than as a cause of corrugation.

The causes set forth by Mr. Frith are in agreement with those given in the paper; we consider that corrugation is a phenomenon of all unlubricated rubbing or rolling friction where there is freedom of motion at right angles to the surface rubbed. Bearings are not usually

Professor Schwartz & Mr. Cunliffe. found to corrugate except where there is freedom for vibration and the absence of lubrication. The seizing of bearings is undoubtedly a first stage of corrugation.

The effects of fluids on sand, referred to by Mr. Cramp, have been studied by us, as also have the rolling effects of wheels on experimental rails of rubber and of gelatinous compounds both free and constricted in their movements in horizontal and vertical planes.

The differences in percentages of slip and skid referred to by Mr. Parrott are due to the effects of flange friction, which depends largely on the position of the weight carried. The tests were carried out on a level track. The presence of corrugation on left- and right-hand rails alternately is referred to in the conclusions given in the paper. The corrugations on trolley wire are not dependent on the length of span nor on the method of suspending the wire. They are probably caused by the skidding of the trolley wheel in a similar manner to the effects obtained on the experimental discs.

The American experience presented by Mr. Davies is at once interesting and instructive and affords a good example of an up-to-date corrugation survey on railway track. The conclusions arrived at are in agreement with views placed on record from time to time by numerous observers; the lateral flow of metal is very pronounced on some of the inner rail sections shown.

We are gratified to find from the correspondence of Continental engineers that the experimental results and the conclusions given in the paper are confirmed by those obtained abroad, particularly by L'Union Internationale de Tramways et de Chemins de fer d'Intérêt local, and we are particularly indebted to MM. t'Serstevens and Busse of the above Union for the interest they have taken in the investigations.

CAPE TOWN LOCAL SECTION.

INAUGURAL ADDRESS OF THE CHAIRMAN,

W. F. LONG, Associate Member.

THE PROGRESS OF ELECTRICITY SUPPLY IN THE CAPE PENINSULA.

(*Abstract of Address delivered* 10*th April*, 1912.)

GENTLEMEN,—It is usual with our Institution for a Presidential Address to take the form of a review of the progress in Electrical Science generally, dealing more particularly with the latest developments.

This subject, however, has often been dealt with by an abler pen than mine, and as there have been no extraordinary developments during the past twelve months, it occurred to me that a review of the electrical industry in the Cape Peninsula since the inception of electric supply here might be of some interest, more especially when considering the developments in the public supply which have recently occurred and are about to take place.

The earliest use of electricity for lighting purposes, of which the author has been able to obtain evidence, appears to have been carried out at the Cape Town railway station and the docks in 1882.

It is not surprising to hear that at this early date only arc lamps were used. They were supplied with energy from two 10-ampere constant-current Brush arc-lighting machines, installed in a building in St. Andrew's Square by the South African Brush Electric Lighting Company.

In addition to eight lamps installed at the railway station certain premises were also lighted, including the Gaiety Bar, the Standard Bar, the Central Hotel, the Fountain Hotel, and one or two shops.

In the year 1886 the company was bought up by the Harbour Board, who removed the generating plant to the dock area, and shortly afterwards added to the generating plant a 25-k.w. Mordey alternator. About this time the Harbour Board took over the lighting of Parliament House, which from 1885 until that date had been supplied from a direct-current steam-driven generator placed in a building in the grounds adjoining the Public Library; and it is interesting to note

that the supply between the docks and Parliament House was transmitted by means of alternating-current at 2,000 volts on bare wires up St. George's Street. The same system of transmission was adopted for the lighting of the new and old Somerset hospitals, which were also supplied from the docks, although the latter was not undertaken until as late as 1894. This original plant in the docks was running as late as 1903, when the new dock power station, alongside the graving dock, was completed.

The railways were supplied with energy from the harbour plant for lighting Cape Town railway station until 1889, when the present railway electrical department was inaugurated.

It is interesting to note that the first work undertaken by the department took the form of train lighting; the suburban trains being lighted by means of accumulators in short vans coupled to the end of the train, and, of course, taken off in the daytime for charging purposes at the headquarters, Salt River Works. This system was inaugurated in 1890. During the same year Salt River railway station (then much nearer the works than the present junction) was lighted also by means of a 100-volt battery of accumulators.

In 1895 the headquarters of the railway electrical department were removed to Cape Town, and a small central station installed. Mather and Platt direct-current dynamos, driven by Davey-Paxman engines of 150 H.P., were provided for charging accumulator vans; and in addition to this plant, Brush constant-current arc-lighting machines were installed, together with a Mordey alternator.

In 1897, the high-tension wires in St. George's Street being considered dangerous, Parliament House was supplied from the railway power station by means of a concentric cable. The Corporation at the time were short of plant, and therefore unable to undertake this supply.

In 1898 and 1899 the plant was extended by means of Mordey alternators direct coupled to Westinghouse engines, but the latter, proving unsatisfactory, were removed in 1900, and replaced with Davey-Paxman engines driving the alternators by means of ropes.

By this time the railway load had been considerably increased, all stations as far as Rondebosch being electrically lighted, in addition to Valkenburg Asylum.

In 1904 the long-series arc-lighting system gave way to short series; 11 lamps being run across 550-volt direct-current machines direct-coupled to Belliss engines of 100 and 200 k.w. respectively.

Public Supply.

The first public electric supply in the Cape Peninsula was that inaugurated by Messrs. Edlin and Stevenson, who secured certain concessions from the municipalities in the southern suburbs. The original plant installed was at Rondebosch, and consisted of four Johnson and Phillips-Kapp direct-current dynamos, belt-driven by two Marshall steam engines. The total plant capacity was 44 k.w., the

system of distribution 3-wire with 220 volts across the outers, and the price per unit charged to consumers 1s. 9d.

In 1893 the Cape Town and Suburban Syndicate acquired the municipal concessions and installed alternating current at Rondebosch, removing their direct-current plant to Wynberg.

In the year 1900 the Cape Peninsula Lighting Company was formed to take over the affairs of the Syndicate.

In 1901, 50 k.w. was added to the Wynberg station, consisting of a Parsons steam turbine direct-coupled to two 25-k.w. dynamos, each of 220 volts (tandem set).

In 1903 the old plants at Rondebosch and Wynberg were shut down and the generating station at Claremont started operations. This plant consisted of :—

One Parsons steam turbine direct-coupled to 3-phase alternator, 3,300 volts, 60 periodicity, 135-k.v.a. capacity.

Two Parsons steam turbines direct-coupled to double-current machines, each 135 k.w.

One tandem set from Wynberg (alluded to before) ; total, 455 k.w.

The statistics available as regards the early years of the suburban electric lighting enterprise are unfortunately very meagre, but it is ascertained that the units sold in the year 1896 (four years after the inception of the undertaking) totalled about 68,000.

In 1911 the units sold reached 329,000 roughly.

The delay in starting a public supply of electricity in the city of Cape Town, which took place as late as 1895, was unfortunate, in that it gave the Gas Company a considerable start.

The system first adopted was the then well-known low-tension 5-wire distribution system, lighting current being supplied at 110 volts between any two adjacent wires, and the 440 volts between the two outside wires being used for the supply of current to motors. This was changed to a 3-wire system during 1897, current for lighting being then supplied at 220 volts ; the supply for motors remaining 440 as before.

The original plant comprised two multitubular boilers, manufactured by Messrs. Simonis and Lanz, of Frankfurt-on-Main ; two direct-current shunt-wound dynamos, with external armatures, of 150-k.w. capacity each, by Messrs. Siemens and Halske ; two 200-H.P. vertical cross-compound engines, by Messrs. Kuhn, of Stuttgart, and two 200-H.P. Pelton wheels, by J. M. Voith, of Würtemburg.

By means of special clutches the dynamos were driven either by the Pelton wheel or steam engines, water for the former being supplied from a reservoir on Table Mountain. In the early stages of the undertaking the steam plant only was used, water being unavailable, but owing to this water-power only being sufficient at any time to drive one dynamo, it soon became necessary to use both steam and

water together. The current generated at this station was conveyed by means of trunk mains to the Dorp Street distributing station, where feeders were run to different parts of the city. A battery of 1,400 amperes' capacity was also installed at Dorp Street, and was provided by Messrs. Siemens and Halske in their original contract.

The whole of this generating plant is still in existence, although the only portions now in operation are the turbine-driven plant at Molteno.

In the early part of 1898 it was found necessary to extend the plant, and in consequence the site in Dorp Street was converted into a generating as well as a distributing station. At this station 300 H.P. was installed; comprising two locomotive type boilers, by Messrs. Clayton and Shuttleworth, of Hyde; one 200-H.P. Bumpsted and Chandler, Crompton high-speed, direct-coupled, direct-current set, and two 50-H.P. steam balancers of similar design. Of this plant the 200-H.P. set has since been used at Dock Road, but is at the moment being removed to make way for a 2,000-k.w. turbo-alternator. At the same time two separate machines were installed at the Molteno generating station, being driven by means of ropes from the existing engines in order that the whole steam plant might be utilised in conjunction with the available water-power.

Towards the end of 1900 still further extensions were carried out, four Davey-Paxman boilers being installed in a temporary wood and iron shed near the site of the present power house. The generating plant in this shed, which was put up temporarily owing to the phenomenal increase in consumption, comprised two 500-H.P. high-speed tandem-compound engines, manufactured by Messrs. Sisson & Co., of Gloucester, direct-coupled to double-current machines by Messrs. Johnson and Phillips.

Owing to the great and growing demand, a Belliss and Morcom engine, direct-coupled to a Mather and Platt generator, was also installed in the temporary shed in the early part of 1903; this has, of course, been removed, and is now running in the Dock Road power station.

The present central power station in Dock Road was officially opened on the 14th April, 1904. The plant follows standard practice for units of the size installed, and so hardly requires description.

The next and probably the last municipality in the Cape Peninsula to open a generating station for the supply of electricity was that of Kalk Bay. The electrical undertaking was inaugurated jointly with the drainage scheme, the sewage of which has to be twice pumped. The plant was installed in August, 1907. The capacity of the station is 300-k.w. and the approximate area of district 3 square miles, the furthest point supplied being 4 miles from the works. At present the plant is worked for about 13 hours per day. Next year it is proposed to run continuously, but from August, 1907, to January, 1910, the plant was only worked 7 hours daily. Up to the present there has been no extension to the generating plant at Kalk Bay.

From the date of the official opening of the Dock Road power

station until 1908, there were no extensions other than the adoption of mechanical stokers, but during the above year, after considerable negotiations, the Government of the Cape Colony and the Cape Town City Council came to an arrangement, by means of which all the requirements of the former, both at the docks, railway, and post office should be supplied from the Dock Road power station.

At this stage it is interesting to sum up the plant at the various central stations in the Peninsula.

We had no less than seven central stations, not including Camps Bay, between the docks and Kalk Bay, the aggregate of which totalled approximately 6,600-k.w., delivering some 7,000,000 units to the various consumers. To allow for distribution losses, assume 8,000,000 units generated, that is to say, the load factor on the whole of the plant installed was only 14 per cent.; in spite of the fact that the tramway power station load factor on plant installed was about 25 per cent. Leaving out the trams and dealing with lighting alone the load factor was only 10 per cent.

To undertake the combined load of the railways, docks, and post office, the Council installed two additional generators of 400-k.w., one of which has been found sufficient for the requirements, including Sea Point; whereas the plant discarded by the Government amounted to over 2,000-k.w. During the two years that the Government's requirements have been generated at Dock Road, the consumption of the two departments has increased by nearly 60 per cent. above that during 1908; whereas the increase in Cape Town public supply between 1904 and 1908 was only 18 per cent. The above increase of 60 per cent., I may say, has been mainly taken by the consumers of Cape Town, Sea Point, and Woodstock, and goes to show how beneficial such a combination is to all parties concerned.

Great changes are about to take place in the electric supply in the southern suburbs. Wynberg has made arrangements to be supplied from Kalk Bay, and it will be seen from the statistics of the latter's undertaking that its output will be increased by approximately 230 per cent., and this, I understand, can be undertaken without increasing the generating plant. Mowbray, Rondebosch, and Claremont will shortly be supplied from the Dock Road power station, and it is interesting to note that, although the total units sold in these three municipalities only run into a little over 200,000 per annum, the taking-over of the area by the Cape Town Corporation has made it possible for prices to be quoted which will lead to an additional sale of energy from the transmission lines to Claremont of some 2,250,000 units. In fact, it is estimated that, as the result of this combination with the southern suburbs and Cape Town, the Dock Road power station will increase its output to 9,000,000 units in 1913 as against an estimate for this year of 6,000,000. To provide for this extra load an additional 400-k.w. alternator at the power station would be ample to supply all the requirements from Sea Point to Kalk Bay; but for reasons of all-round economy it has been decided to install a 2,000-k.w. turbo-alternator and

a 1,000-k.w. rotary converter, which under normal conditions will supply the whole requirements of the Peninsula at any rate for the next two years. The total plant installed will still be less by about 500-k.w. than the total installed in the Peninsula for purposes other than tramways in 1908, and at the same time will include 100 per cent. spare, in view of the fact that the present reciprocating plant will only be used as a standby.

If any one has any doubt of the economy that must follow a combination of the various electrical undertakings in the Cape Peninsula, the above figures are, I hope, sufficient to place the matter beyond such doubt.

Finally, it would appear, in view of these recent developments, that the electrical industry in the Cape Peninsula is now likely to make rapid strides, which I sincerely hope will be to the benefit of all those interested therein.

Increase in Consumers' Lamps, etc., Quinquennially in the Cape Town Corporation Electricity Department since its Inception.

Date.	Motors. Horse-power.	Consumers.	8-c.p. Lamps.	Revenue.
1895	No available data	20	2,100	—
1900	No available data	538	37,100	£28,618
1905	2,140	1,332	95,300	67,476
1910	3,623	1,600	137,578	65,279
1911	4,330	2,021	167,774	68,206

THE DIESEL ENGINE FROM THE USER'S STANDPOINT.

By WM. J. U. SOWTER, Member.

(*Paper received 6th February, and read before the* DUBLIN LOCAL SECTION, *18th April*, 1912.)

The Diesel engine is coming into such general use for the purpose of the generation of electrical energy that a few notes on its advantages, cost of running, and maintenance may be of interest.

Although several papers have been written on the subject, most of the conclusions arrived at are based on estimated results, and it is, therefore, the intention of the author to discuss the matter from the user's standpoint, quoting as far as possible results obtained in actual practice.

Cooling Water.—The quantity of cooling water required is considerably less than that required by suction gas or steam plants. With an inlet temperature of 50° F. and an outlet temperature of 140° F., about 3 gallons per B.H.P. are required. Where water is an expensive commodity, *i.e.*, water from town mains, it may be used repeatedly if passed over a small cooling tower, when only the water lost due to evaporation and leakage will actually be consumed. Taking the case of a 250-B.H.P. engine, and assuming the loss due to evaporation and leakage to be 10 per cent., the cost of water at 6d. per 1,000 gallons will amount to 0·45d. per hour. It is apparent, therefore, that generating stations using Diesel engines can be located in populous districts, removed from rivers or canals, if a town water-supply is available, and the cost of cooling water will be a negligible item. This is an important consideration, as the generating station can be located in the centre of the area of supply, which may result in a considerable reduction of the cost of the distributing system.

Fuel.—The Diesel engine is capable of working satisfactorily and economically on a wide range of fuels without any alteration or adjustment.

The standard fuel is crude Texas or Roumanian oil, which may be purchased at prices ranging between 35s. and 70s. per ton, the price being lower near large ports, where the cargoes are discharged in bulk from tank steamers, and increasing according to the distance it has to be transmitted in tank wagons by rail or road, or, in other cases, tran-

shipped. The oil can be purchased in London at about 40s. per ton, while in Bray the present price delivered into our tanks is 58s. 6d. per ton. In the latter case the oil is imported in wood barrels; but should a considerable demand occur in this country the oil merchants would, doubtless, stock a bulk supply, which would naturally result in cheapening the supply to consumers.

The following is a specification of a suitable oil which the author has adopted with satisfactory results:—

1. The oil shall be crude, refined, or a residue of petroleum.
2. It shall be free from tar, bitumen, or solid hydrocarbons; it shall also be free from sand, fibrous matter, or foreign solid impurities.
3. The oil shall not contain more than one-half of 1 per cent. of water, nor 1½ per cent. of sulphur, and shall be free from acid.
4. The viscosity shall be such that the oil will flow in a continuous stream with 1 ft. head through a ½-in. copper pipe 6 ft. long without heating.
5. The calorific values shall not be less than 18,000 B.Th.U. per lb.

Many other liquid fuels may be used, such as residue shale oil, gas-works tar oil, or creosote oil.

Attention has frequently been drawn to the fact that suitable oils have varied widely in price from time to time. Much of this variation, however, has been caused owing to the scarcity of tank steamers for the conveyance of the oil to these shores. This, however, is a difficulty which is being rapidly overcome, and there seems every probability that the market is now fairly settled.

Running Costs.—Contrasted with steam plant, there is but little difference in fuel consumption per B.H.P.-hour between large and small Diesel engines, nor does the fuel consumption increase largely per unit of energy as the load is decreased on the engine. It is well known that a large steam engine running at light load is grossly inefficient, the fuel required to maintain steam pressure in the boilers and to run the engine light, together with the necessary auxiliaries, being out of all proportion to the work done; also, a small steam engine requires many more pounds of steam per h.p. to run it fully loaded than does a large one. In addition to these considerations there is the serious question of stand-by losses, which are very great indeed with steam plants, while they are absolutely non-existent where the Diesel engine is used.

It is apparent from the foregoing remarks that it is unnecessary from the point of view of fuel economy to install large engines when a greater number of small engines will suit the circumstances of any particular case better, desirable as the former procedure may be so far as capital cost per kilowatt of plant installed is concerned.

The following figures show the cost of fuel per unit generated with

oil at the prices mentioned, and at various loads, for a 50-B.H.P. engine coupled to a 33-k.w. generator :—

Load.	Dynamo Efficiency.	Price of Fuel per Ton.			
		40s.	50s.	60s.	70s.
	Per Cent.				
Full	88	0·161	0·201	0·242	0·281
Three-quarter	86	0·178	0·210	0·252	0·295
Half	83	0·208	0·261	0·314	0·365
Quarter ...	78	0·307	0·384	0·462	0·538

These figures are not merely manufacturer's "paper" figures, and the author is in a position to vouch for them personally, he having obtained similar results after repeated tests at irregular intervals. On larger plants the costs would be some 10 to 20 per cent. better, depending upon the size of the plant.

Figures such as the above clearly demonstrate the great advantages this type of plant offers for use in small generating stations.

Many small stations to-day are labouring in the endeavour to produce cheap units from dear coal with inefficient steam plant, and doubtless there are many instances in which it would pay the owners of such undertakings to scrap the whole of their steam plant, installing instead Diesel engines.

Such a change, however, is often a matter of considerable difficulty, particularly in those cases in which loans can only be contracted under statutory authority, such as is necessary in the case of municipal undertakings, who, having obtained sanction for a loan for the initial plant, are debarred from obtaining further loans (excepting for extensions) until the original debt has been paid off. Even under such conditions it would often be a sound financial policy to pay off the balance of the outstanding debt and to obtain a fresh loan for highly efficient plant, which would eventually convert a losing into a paying concern.

Steam plant, if not properly maintained, becomes more and more uneconomical as time goes on ; still the plant continues to run as though all were in order, but with an increased fuel consumption ; on the other hand, internal combustion engines—and particularly the Diesel engine—must be maintained in thorough good order, otherwise there will be great difficulty in getting them to run at all ; therefore, those in charge of such plants are bound to see that they are carefully attended to, and when in good order the fuel consumption must always be normal, while, as we have seen, steam plant, if in bad order, can still

be run, but at great expense as regards fuel. This characteristic of the Diesel engine is, therefore, a valuable one, as the engineer-in-charge, knowing that his plant will only run indifferently if neglected, naturally takes care to see that the plant receives the attention required, as a shut-down due to neglect probably would be far more serious to him than an enhanced coal bill, which might pass unnoticed.

In connection with this matter, it may be pointed out that in small steam-driven stations there is a certain amount of difficulty, and it requires constant supervision and a certain amount of labour to keep a strictly accurate record of the fuel consumption day by day. Even when it has been definitely ascertained that the consumption per unit has increased, there still remains the task of finding which portion of the plant is at fault.

The following points need examination :—

1. The quality of the coal.
2. The efficiency of the stokers.
3. The condition of the boiler flues and settings.
4. The proper regulation of the draft to secure efficient combustion.
5. The cleanliness of the boilers and tubes, economisers, etc.
6. The condition of the main and auxiliary engines, pumps, condensers, etc.

Now with a properly arranged station where Diesel engines are employed the fuel consumption may be ascertained with absolute accuracy hourly if desired, and thus it may be said that the plant is always under test.

The arrangements which the author has adopted to secure this end are as follows :—

The fuel oil is stored in a tank of sufficient capacity to hold several tons. From this tank a distributing pipe is laid to a small tank fitted just above each engine, and the quantity of oil delivered to each small tank is controlled by cocks having removable keys in order that the tanks may only be filled under the supervision of a responsible person, the bulk supply being under lock and key. Each tank is fitted with a gauge-glass, and a scale calibrated in gallons, in order that the quantity of oil in the tanks may be ascertained at any time. Similarly, each generator is fitted with an integrating wattmeter. Therefore, if the energy generated during any particular time is compared with the quantity of oil consumed during the same period, the fuel consumption per unit generated can be determined with a considerable degree of accuracy and with a minimum amount of labour.

Capital Cost.—The capital cost of a Diesel engine direct-coupled to a generator is considerably greater than a gas or steam-driven generator of similar capacity, but when the costs of complete plants, comprising either gas or steam, are compared, there is but little difference in the price per kilowatt. A Diesel station, however, requires

less land and buildings than similar stations employing steam or gas plant, so that the difference, if any, is in favour of the Diesel plant.

The following are approximate prices for small plants, delivered and erected on purchaser's foundations complete with oil storage tanks, piping, etc., and may be taken as fairly representative :—

Size in Kilowatts.	Price.	Price per Kilowatt.
	£	£
100	1,950	19·5
150	2,600	17·3
200	3,260	16·3
300	4,380	14·6
400	5,300	13·3

Probable Life of Diesel Plant.—The useful life of generating plant is an important factor for consideration, and one which must of necessity be taken into account in considering the working costs of any undertaking.

It has been said from time to time that the stresses set up in an engine of the Diesel type are extremely violent, and in order to support that view, attention has been drawn to the heavy and solid construction of the engine. As a matter of fact, however, the stresses are no more severe than those met with in ordinary gas-engine practice. The solidity of the parts is really due to the fact that the engine is single-acting, and only gives one impulse per two revolutions as compared with two impulses per one revolution in the case of the single-cylinder, double-acting steam engine; hence the parts must necessarily be proportionately strong. It is doubtless within the memory of many that, when a once famous single-acting steam engine was first introduced, considerable trouble arose from the repeated breakage of crank-shafts. The cause was probably owing to the fact that the designer had not fully realised that double pressure was put on each crank once per revolution instead of half pressure twice per revolution, as in the case of the ordinary double-acting engine. In other words, the driving parts of, say, a 50-B.H.P. Diesel engine require to be the same strength as similar parts of a single-cylinder double-acting steam engine of 200 B.H.P. This fact having been fully realised, there is no reason why the Diesel engine should be more liable to breakdown than the steam engine.

The author is of opinion that the life of the Diesel engine should be equally as long as that of a well-built steam engine. The only expensive part likely to require replacement is the cylinder liner. It

is essential that the compression should be maintained, and all the author can say on this point at present is that he has had an engine running for over two years, and that no appreciable wear of either the liner or piston rings has yet occurred. It appears, therefore, that the life of the liner may be computed at at least ten years. The valves are fitted into removable casings, which can be renewed at quite a small cost.

As most of the other parts, such as springs, pump plungers, air-pipes, and so on, are quite light, cheap, and easy to replace, it appears that the cost of maintenance of this type of engine must be very much less than a complete steam plant, considering that the engine takes the place of a steam engine, boiler, steam pipes, feed pumps, economiser, chimney, and the numerous small items incidental to a steam installation, all of which require frequent attention.

Practical Notes on Running.

Although the Diesel engine possesses considerable advantages, it is undoubtedly true that in order to secure reliability first-class attention is necessary.

The various points which need regular attention can only be ascertained from practical experience, but, when that experience has been gained and intelligently applied, there is no reason why the running and reliability of the plant should not be at least equal to steam, and vastly superior to gas plant.

Attendance.—Smooth running very largely depends upon the man in charge of the plant, and it may safely be said that 90 per cent. of the trouble experienced in the running is due to the neglect of attendants. The majority of workmen are extremely conservative, and do not take kindly to innovations. As the running and maintenance of internal combustion engines is essentially different to that of steam plant, it is always better to secure the services of men who are accustomed to similar plant than to employ men who have spent their lives among steam plant. The latter in most cases do not trouble to think out for themselves the various problems which arise in their daily work under the new conditions, while there is no doubt that the class of plant we are now discussing requires sympathetic handling in order to secure successful results. In spite of statements to the contrary, therefore, it may be assumed that Diesel engines require considerable supervision, and that it is advisable to employ men of skill and experience rather than mere labourers. Even taking this matter into consideration, the cost of labour on moderate-sized plants is substantially less than that necessary with steam plant.

The following remarks may be of interest to members who are or may be called upon to supervise the running of Diesel engines:—

Lubrication.—It is of importance that a suitable grade of oil should be chosen; the oil must be a pure mineral one with a high flash-point. Suitable oil, however, is not necessarily expensive; the author is using ordinary crank-chamber oil, costing 1s. 5d. per gallon, with perfectly satisfactory results.

Although it is claimed that the cost of lubrication of Diesel plant is no greater than that of a good steam engine, such is not the author's experience, the cost in his case being about 50 per cent. greater.

While efficient lubrication is essential, the use of an excessive quantity of oil should be avoided. The piston and gudgeon pin are lubricated by a pump, which forces the oil through a hole in the liner and piston to the pin, and also through an angular space between the liner and cylinder casting. There are generally about six holes, about $\frac{1}{32}$ in. in diameter, drilled through the cylinder at this point, and through which the oil is forced to meet the piston. Should the oil be dirty, or contain carbon, these small holes readily become blocked, cutting off the supply of oil to the piston.

Oil after collection from the crank pit contains a certain amount of carbon, and should be placed in a settling tank, preferably heated by a steam coil, or, if a supply of steam is not available, an electric heating arrangement of some kind. After a sufficient time has elapsed for settling, the oil should be drawn off from the top and passed through a good filter before use. The author has found that it is practically impossible to remove the whole of the carbon from the oil, and consequently if the oil is used repeatedly, more and more carbon will be fed into the cylinders and other parts until there is a sufficient accumulation of carbon to cause a stoppage of the lubricating passages.

As a seizure of the piston might cause serious damage to the engine, and as it is naturally necessary to economise in lubricating oil as much as possible by using filtered oil, the author recommends that the piston should be drawn every six months, and the lubricating passages cleaned.

The carbonisation of oil may also cause trouble in the air-compressor cylinders. Before the author realised this possibility, filtered oil was always used in the compressor, and probably to excess. In course of time the high-pressure air-pipe leading from the compressor to the intercooler blew off at the joint, when it was discovered that the pipe was completely blocked with solid carbon.

Valves.—Owing to the high compression which must be maintained, it is necessary to keep the valves quite tight, otherwise leakages will occur reducing the compression, which renders it very difficult to start the engine, and when started proper combustion of the fuel is not secured. The author suggests a system whereby each valve is examined and ground in at stated intervals. He has found that under the conditions in which he is working the valves will run without any attention for the following periods :—

Exhaust	600 hours
Air	2,000 "
Fuel	600 "
Starting	One year

In order to ensure that the valves are maintained in good order, the running hours of the plant should be logged and a record kept of the

date each valve was examined and ground in ; it is then an easy matter to see when each valve is due for attention. Spare valves and casings are supplied with each engine, which can be changed in a few moments, and the valve and casing removed can be ground in at the attendant's leisure.

The needle or fuel valve is so adjusted that the fuel spray is blown into the cylinder two or three degrees before the crank reaches the top centre on the compression stroke. It is very important that this valve should be properly set and quite tight ; if there is any leakage fuel will be admitted at the wrong time, resulting in irregular running of the engine.

The pulveriser is liable to become choked if the fuel oil is dirty and insufficiently filtered ; it should, therefore, be examined and cleaned at the same time as the needle valve. A clogged pulveriser may cause difficulty in starting or reduced output owing to insufficient fuel passing to the cylinder.

Air Compressor.—A considerable quantity of vapour is carried into the compressor, the quantity depending upon the humidity of the atmosphere. When the air from the compressor is cooled in the intercooler the vapour is condensed and, unless the drain on the intercooler is blown down frequently, water is carried over into the air-storage receivers. The water naturally causes rusting of the interior surfaces and also, as the air in the bottles will be consequently damp, rusting of the steel pipe leading to the starting valve may occur ; the rust is carried along from the receivers and pipe to the starting valve, where it will accumulate, eventually causing the starting valve to stick. If this occurs the contents of the bottle may be lost before the valve can be shut. The only precaution necessary to avoid this annoying experience is to see that the intercooler drain is blown down at regular intervals, say very half-hour, particularly in damp weather. The air-storage receivers are provided with syphons and drains, and should be drained every day.

The compressor high-pressure suction and delivery valves require grinding in about every six hundred running hours, and the low-pressure valves about every two thousand hours. If the intercooler drain is not blown down frequently enough, or if too much lubricating oil is used, the valves may hang up. This can usually be remedied by repeatedly blowing down the intercooler drain until the accumulation of oil and water is removed.

It is well to draw the compressor pistons every six months and clean off the accumulation of carbonised oil which is deposited on the top. It is also advisable to clean the air inlet and passages to the low-pressure valves at the same time.

Starting Air.—Where only one engine is installed in an isolated position the loss of the air in the storage cylinders would be a serious contingency, as without such a supply it would be a difficult matter to start the engine ; in fact unusual means would have to be adopted. The following are some of the methods recommended :—

1. If the engine is driving a dynamo, and there is a storage battery on the premises, the dynamo may be run as a motor to drive the engine and compressor. As soon as the pressure in the blast receiver reaches about 700 lbs. pressure the fuel supply may be turned on, and if the engine is in order it will start off. This method is not recommended unless care is taken to see that the normal discharge rate of the battery is not exceeded.

2. The storage bottles may be charged from cylinders of oxygen* or carbonic acid gas. If the latter is used the cylinders and pipes should be warmed in order to prevent solidification of the gas in the pipes.

If the engine is erected in a locality where it is unlikely that either of the above facilities will be available, it is desirable that a small independent compressor, coupled to an ordinary oil engine, should be put down as a safeguard.

In stations where two or more Diesel engines are installed there is no necessity to take any precaution other than to couple up the various starting receivers in such a manner that any set can be charged from any engine.

The loss of starting air is a very uncommon occurrence. It usually arises from the carelessness or ignorance of the attendants, it being most unusual for the air to be lost owing to leakage.

Defective Starting.—This difficulty is generally due to one of the following causes :—

1. Low compression.
2. Defect in oil pump or oil supply.
3. Incorrect adjustment of fuel, air, or exhaust valves.

Low compression is most commonly due to a bad condition of the valves, and an indication that they require grinding in. It may happen that if the engine is overheated, due to defective water circulation or overloading, the valve casings may be distorted, resulting in a leakage between their joint faces and seatings in the cylinder head. If no leakage is apparent from examination, the application of the indicator will speedily determine whether the compression is low.

The fuel oil-pump is usually so arranged that it can be disconnected from the engine and fitted with a temporary means of operating it by hand for the purpose of pumping up the delivery pipes with oil after they have been disconnected for any reason. Also, the delivery pipe from the fuel pump is fitted with a by-pass worked from the starting lever controlling the fuel- and starting cam levers. The by-pass is so arranged that when the engine is started on compressed air no oil is delivered into the fuel-valve casing until the starting lever is put into the running position. If no such by-pass were fitted the needle-valve casing would be filled with fuel pumped in while the engine was

* In view of the recent accident at Bray the use of compressed oxygen for this purpose should be strictly prohibited.

running on compressed air, and when the starting lever was thrown into the running position, and the fuel valve opened at its proper time, too large a charge of oil would be admitted to the cylinder, which might cause damage. If it is suspected that fuel oil is not reaching the cylinders the fuel pump should be overhauled and its valves, as well as the by-pass valves, examined and ground in if necessary. If the by-pass valves are not perfectly tight oil may leak away instead of passing into the fuel valve, when starting would, naturally, be difficult, or even impossible.

The setting of the needle valve may readily be tested by barring round the engine until the crank is near the firing centre; compressed air should then be admitted to the blast pipe, the indicator cock opened, and the engine slowly barred round until air commences to issue from the indicator cock. This is the point at which the fuel valve commences to open, and should correspond with the maker's setting marks.

The air and exhaust valves should commence to open at the proper time, and in order to ensure this most makers stamp on the engine the clearance there should be between the cams and rollers at a marked point. These clearances should be checked periodically, and adjusted if necessary.

If the engine is kept in good order, and the above points carefully attended to, there should be no difficulty experienced in starting easily and certainly.

Exhaust.—The exhaust should be smokeless; black smoke may be emitted if the blast pressure is too low, or if the engine is overloaded. If all is in order the exhaust should be colourless, indicating perfect combustion of the fuel.

The exhaust gases escape from the engine at a pressure of about 40 lbs. per square inch, and it is necessary that adequate measures should be taken to allow the escaping gases to expand gradually, or nuisance may be caused to the surrounding neighbourhood. For most situations the cast-iron silencers provided with the engines will be quite effectual, but the author had some trouble, due to the fact that private residences are in close proximity to the works. The exhaust, therefore, was led to a large concrete pit, which removed all cause for complaint. It is the intention of the author to lead the exhaust from a 150-B.H.P. engine, shortly to be installed, to the base of an existing chimney-stack 120 feet high, which should deal with the difficulty in an effectual manner.

In steam-driven stations, where extensions are carried out by adding Diesel engines, the use of exhaust boilers would be a further source of economy, enabling the waste heat from the exhaust of the Diesel engines to be utilised on the steam side. Exhaust boilers also are a useful means of providing hot water in factories where such is required for the process of manufacture and Diesel engines are installed for the provision of the necessary power required.

Discussion.

Mr. S. L. R. Price: When my Council in Pembroke decided to install a Diesel generator set for their next extension, their decision was more or less governed by information which I had previously gathered from various works that I had visited in different parts of the country. The concensus of opinion certainly appears to be in favour of Diesel engines, though they are by no means without their troubles, and in my opinion it would be most unwise to supply any but thoroughly experienced men in handling them, the "handy man" being a decidedly risky experiment. While at one maker's works I had an opportunity of witnessing the final stages of erection of an engine (300-B.H.P. as far as I can remember), and then saw it run up to full speed within 5 minutes of starting it up. It ran extremely smoothly for a matter of half an hour before shutting down for examination. This struck me as somewhat inconvenient in some ways, for there being apparently no such thing as "crawling" an engine, as might be done in the case of steam, in looking for defects one has to take a good deal of risk in running up a set. One of the weak points about a Diesel engine appears to be the gudgeon pin, which is situated within the zone of greatest heat, and one would far prefer to see the ordinary cross-head adopted. This is now done, I believe, for certain types. Another source of trouble appears to be the proper cooling of the cylinders and cylinder covers. Unless watched, scale is liable to form in the circulating chamber, and troubles result. A cracked cover is not uncommonly met with, I believe. Inspection doors are now fitted in the cylinder jackets by many makers, with a view to preventing trouble from the formation of scale. When these engines are required for use in residential districts, vibration is likely to cause trouble and annoyance, but doubtless this will be got over in time. Mr. Price.

Mr. A. E. Porte: I would suggest that 140° F. is too high a temperature for the jacket water. I prefer an outlet temperature not exceeding 100–110° F. I have had trouble due to the fuel oil thickening in the pipes, and have had to warm the pipes. Diesel plant, if properly looked after, should last at least twenty years. In my own experience suction plant is most satisfactory and reliable. I should like to have some further particulars of the cost of lubrication. The question of moisture in the air compressor is interesting. Has the author considered the question of an automatic drainage similar to an ordinary steam trap? The best means of dealing with noise from exhaust is to turn it into a pit filled with broken stones. The capital cost of producer plants and engines is practically the same as that of Diesel engines. In conclusion, I would strongly advocate forced rather than natural circulation of the cooling water. Mr. Porte.

Mr. T. Tomlinson: The Diesel is a very finely-built engine, with small clearances, and cannot be run without skilled supervision. Pre-ignition is quite possible if there is any leakage at the fuel valve. The Mr. Tomlinson.

Mr. Tomlinson.

Diesel engine is not very economical at light load, as the mechanical efficiency is bad. The consumption curve follows a straight-line law. When anthracite can be obtained for half the cost of fuel oil, then the cost per B.H.P. for suction gas and Diesel plants is practically equal. I consider that the Diesel engine has a future before it if used in generating stations for peak loads, thus reducing stand-by losses. Personally, I do not think any engineer in Ireland should think of installing Diesel engines if he were near a bog and knew of Mr. Robb's success at Portadown.

Mr. Aston.

Mr. T. ASTON: While it is possible to use tar oil as fuel it is necessary to specially adjust the settings of the valves, and it should be noted also that the calorific value of this oil is lower than crude petroleum. My firm has collected figures as to the cost of repairs to some 10,000 H.P. of engines, and found that it worked out at under 1s. 6d. per B.H.P. per annum. The cost of lubrication should not exceed that of steam practice. A guarantee of 3 grammes of oil per B.H.P.-hour is frequently complied with. Loss of starting air rarely occurs, but there is no limit to the amount of extra storage which can be installed. At Athlone, with anthracite at 30s. and oil at 60s., the Diesel costs are substantially lower; while at Letchworth, with anthracite at 32s. and oil at 42s., the costs per unit generated are: for gas, 0·382d.; and for Diesels, 0·155d.

Mr. Home.

Mr. S. T. HOME: The stresses which occur in the Diesel engine are far more severe than in gas engines, especially on the crankshafts. If there is a slight leakage past the piston of a Diesel engine, the efficiency drops seriously on account of imperfect combustion, due to reduced temperature of the compressed air. For such high pressure a heavy-bodied lubricating oil is necessary, and there is no doubt that the cost of lubrication of any internal combustion engine is higher than steam plant. Water containing lime should be treated before being passed through the jackets, or encrustation will occur: hydrochloric acid often has to be used to dissolve such deposits. As regards fuel costs, I am of opinion that the only reasons why electrical engineers consider internal combustion engines in preference to steam plants are fuel economy and less attention being required.

Mr. Sandford.

Mr. P. SANDFORD: I might mention that my firm has recently secured an order for four 4,000-H.P. Diesel engines in competition with tenders for steam turbines. The absence of standby losses, the very high fuel economy, the small floor space required, and the rapidity with which the engines can be put on load no doubt account for this decision in favour of the Diesel engine.

Mr. Sowter.

Mr. W. J. U. SOWTER (*in reply*): As regards the life of Diesel plant, the L.G.B. have granted my Council a loan for the first engine I installed for a period of eighteen years. The question of mean pressure is really determined by the capital cost and speed, but high-speed engines might give trouble by wear of the valve-faces due to pounding of the valves, as stronger springs would be necessary. I

agree with Mr. Price regarding the gudgeon pin, although I have never had any trouble with this part. The substitution of a cross-head would doubtless be an improvement, but this again is a matter of increased cost. I have had some trouble due to overheating, but this was due to the engine having been overloaded; I consider that ample inspection covers and means for washing out are a necessity. As I have plenty of cooling water available, I run as much through the engine as possible. The figure of 3 gallons per B.H.P. with a final temperature of 140° F. is obtainable, but it is better to work at a lower temperature if possible. Oil pipes from storage tanks should be of ample size. The actual cost of lubrication over one year's working was 0·014d. per unit. The automatic draining of compressor coolers offers some difficulties. Pre-ignition might be possible if the needle valve was allowed to get into a very bad state, but should never occur if the engine received fair treatment. In a gas engine the fuel is burnt almost instantaneously, while in a Diesel cylinder the fuel burns for an appreciable period, and therefore the heat can be removed by the cooling water more effectively, while, as the thermal efficiency is higher, less fuel is used; consequently a Diesel cylinder can give a larger output than a gas engine cylinder of the same size. In conclusion, I may say that if water is present in the fuel oil, trouble may be experienced. On one occasion we could not get the engine to start off. Investigation showed that the fuel pump was half full of water, and the pump was delivering water instead of oil to the cylinders. Mr. Sowter.

WEIGHT EFFICIENCY OF ELECTRIC MOTORS AND OF PRIME MOVERS.

By W. B. HIRD, Member.

(*Paper received 6th March, and read before the* SCOTTISH LOCAL SECTION, *11th April*, 1912.)

SUMMARY.—Comparison of weight efficiencies of electric motors and of different types of prime movers. Choice of unit for comparison. General law connecting weight and output adopted as a working hypothesis. Graphs embodying the results of investigations on steam engines, steam turbines, gas engines, oil engines, petrol engines, water turbines, and electric motors.

Individual manufacturers have, I suppose, at all times been in the habit of comparing the cost, design, and weight of their manufactures with those of similar articles turned out by their competitors.

The suggestion here made is that such comparisons, and others of a like nature, might be extended to include different types of machinery. An important branch of the biological group of natural sciences is comparative anatomy, in which the structures and organs of different animals and plants are compared, their similarities and differences investigated, the evolution traced from lower to higher types, and some explanation of the differences observed is sought for. A systematic investigation on these lines of the methods employed and the results obtained in different branches of engineering would certainly be interesting and might prove to be of great practical value. The directions in which an investigation might be made are numerous. As an instance, one might consider the factors of safety which it is considered good practice to employ in determining the strength of various structures used for dissimilar purposes. Does the constructional engineer, having calculated the strength of his materials and the stresses on his structure, consider it safe to use the same factor of safety for his girders as the mechanical engineer will employ to determine the dimensions of various parts of his machinery? Or, again, in the different classes of machinery used to obtain mechanical energy, what is the relation between weight and the power obtained or between weight and efficiency? Other lines of investigation will readily suggest themselves.

Of the differences in practice which would certainly be observed in any such comparison very many are without doubt justified by the circumstances of the cases. The different purposes for which a machine is to be used will frequently require that some one quality or

another be obtained at the cost of serious sacrifices in other directions; but I venture to think that a good many of the differences which would become apparent in a systematic comparison of present-day practice in different branches of engineering would turn out to have no real justification, but to be due to the conservative attitude of the designer.

It is intended in what follows to consider on as general lines as possible one only of the suggested lines of investigation, namely, the relation of weight to output in electric motors and in various types of prime movers. If any such comparison is to be of any value it must rest on a broad basis and include figures from the greatest possible variety of cases. On many points of design reliable information would be difficult to obtain; this initial difficulty does not arise in the case of the proposed investigation, where the desired particulars are to be got quite readily.

The inclusion of the electric motor is of course of special interest to members of this Institution, and if the electric motor is not strictly a prime mover it exactly replaces one for the consumer taking his supply from public mains; and if the time ever comes when a method is desired of converting the stored energy of coal into electrical energy, the electric motor will become a prime mover in the strictest sense of the term. The information usually given in manufacturers' catalogues, and therefore easily available, is sufficient to allow of very interesting comparisons in the matter of weight. The particulars made use of are the weight of any given machine, its rated output in brake horse-power, and the revolutions per minute at which this output is obtained.

To arrive at the results which follow, a large mass of figures as to the weights of the electric motors, steam engines and turbines, gas engines, oil engines, petrol engines, and water turbines was examined and analysed, and I have to acknowledge the kindness of many manufacturing firms, too numerous to mention individually, who have given me information as to their machines.

The size and therefore weight of an engine or motor naturally increases with the power at which it is rated, but it decreases with the speed at which this power, this rate of giving out energy, is obtained. Roughly speaking, if the speed of any individual engine or motor be varied, the power to be obtained from it will vary directly as the speed. The variation of speed will be obtained by different methods, according to the type of motor under consideration: in an electric motor it may mean so considerable an alteration as is involved in totally new windings, in a steam engine it may involve only a change in the governor. Also the variation obtainable will be restricted within strictly defined limits, but within the permissible range the speed variation will be obtained without material alteration in the main dimensions of the motor, and therefore without material alterations in its weight.

In manufacturers' catalogues an engine or motor is frequently rated at several different outputs, each with a corresponding speed, and the powers in such cases are invariably found to be, within a close approximation, proportional to the speed.

It is only to be expected that this should be so; if the power per revolution is constant the torque will remain the same, the strength of the parts must therefore be approximately constant, and since about the same quantity of working substance will be required at each revolution, the capacity of the cylinders, the conductors, etc., according to the type of motor considered, must remain about the same; it is therefore quite natural to find that the dimensions of any type of motor do not greatly vary, however the horse-power be varied, provided the speed varies proportionately

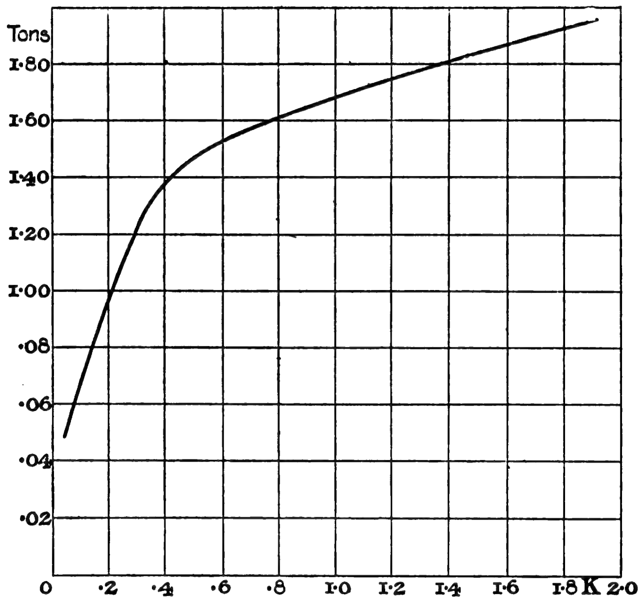


FIG. 1.

It is proposed, therefore, to take as a basis of comparison the horse-power divided by the speed, this fraction being the same, or approximately the same, for any individual machine; then, taking any line of motors, a graph can be plotted of weights against the fraction—

$$\frac{\text{Horse-power}}{\text{Revolutions per minute}}.$$

This fraction is represented throughout this paper by the symbol K, and may be called the output constant. A graph, such as above described, is shown in Fig. 1. This graph shows the relation of weight to output for a group of continuous-current electric motors. A large number of such graphs might be prepared for motors by different

makers for gas engines, steam engines, etc., but in order to obtain any clear understanding of the results so obtained a step further is required, and an endeavour has been made to find some general rule or formula connecting the weight with the output constant K.

If the constant K is divided by the weight in tons, and a graph of the results plotted to base K, the graph will show what output in brake horse-power per revolution is being obtained from each ton of material used, and it is found that in a large number of cases the points thus obtained for one line of machines lie very nearly in a straight line. It is true that another set of machines, perhaps even by the same maker, will give a graph different from the first one both in inclination and in its intercept on the axis; but in so many cases is it found that a straight line can be drawn through the points, that it is fair to assume that if all the parts of a machine were made strictly of the best size and of a uniform line of design, the points would fall on a straight line. In order, however, to meet the requirements of manufacture, identical parts are in some cases used for two or three different sizes of machine; the same bearings, bed plates, and other similar parts are used for perhaps several sizes out of a line of machines in order to save the multiplication of patterns and to facilitate standardisation of manufacturing processes; the natural result is that some machines are heavier than absolutely necessary, whilst others fall somewhat below the standard set for the whole line in the strength of some of the parts, and are therefore somewhat on the light side. From these and other accidental differences in design it is to be expected that in plotting curves of weight considerable variation from a smooth curve will be at times apparent, but such departures may be considered as accidental, and do not detract from the value of any working hypothesis which may be deduced from the general trend of the curve.

In the majority of cases where the figures for a manufacturer's line of engines or motors were available the general direction of the points obtained by plotting the horse-power divided by K against K were distinctly in a straight line, and the departures which occurred from this were irregular, and showed no indication that any smooth curve could have been drawn through the points and have represented their general position with greater accuracy than did the straight lines; and although cases did occur where the results of a line of machines might have been better indicated by a curved line, this was found to be as often convex to the axis as concave, so that, on the whole, for none of the types investigated did it appear that a straight line did not fairly represent the general trend of the results obtained.

General results such as are here aimed at require to be represented in a form easily grasped, and as a result of the above considerations it was decided that they would in this case be best represented by a series of straight-line graphs showing the average result for each type of motor investigated. The process of obtaining these was carried out thus: Taking any one type of motor, say, the electric motor for the sake of example, lists of output, revolutions per minute and weight

in tons were prepared from the figures of as many manufacturers as possible. The brake horse-power divided by the revolutions per minute gave the constant K. This was used as the abscissa and K/tons was plotted as ordinate; through the mean position of the points thus obtained for any one line of machines a straight line was drawn. Several lines of motors investigated therefore gave a number of such straight lines. The position of each of these lines is fully determined by noting its inclination to the horizontal axis and its intercept on the vertical axis; the mean value of the intercepts was calculated, also the mean value of the inclination, and with these constants a straight line was drawn indicating the mean value of the horse-power divided by the revolutions per minute which is being obtained in

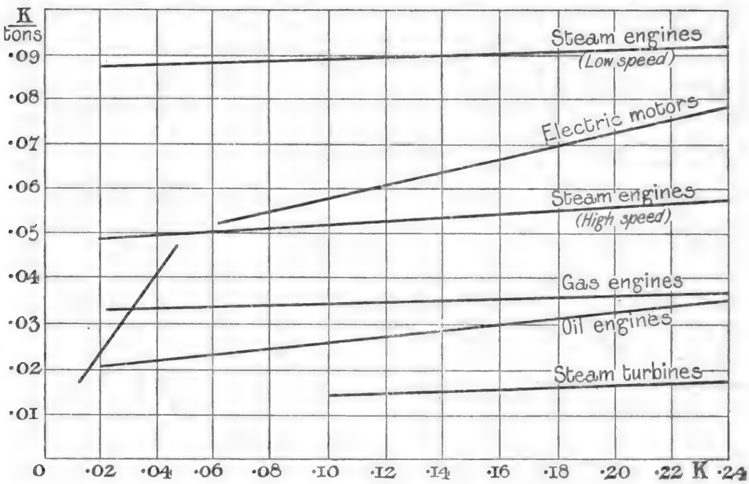


FIG. 2.

practice to-day for the employment of one ton of material. Such lines for the different types dealt with are gathered together in Figs. 2, 3, and 4, and some of the results are also shown in tabular form below.

Fig. 3 embodies the principal results obtained, but very many of the cases dealt with gave a value of K below 0·2, and therefore not easily plotted on the same diagram.

Fig. 2 is drawn to an enlarged scale, giving the results for motors having a value K less than 0·2.

In the case of the water turbine the slope of the weight efficiency curve was so much steeper than for the other engines investigated that a different scale was required, and the water turbine graphs are therefore given in Fig. 4.

All these lines have the same general characteristics—they slope upwards from left to right; that is to say, as we pass upwards from the

smaller to the larger members of any lines of machines, the weight efficiency goes up and a larger value of horse-power per revolution is obtained for each ton of material used. No great accuracy can of

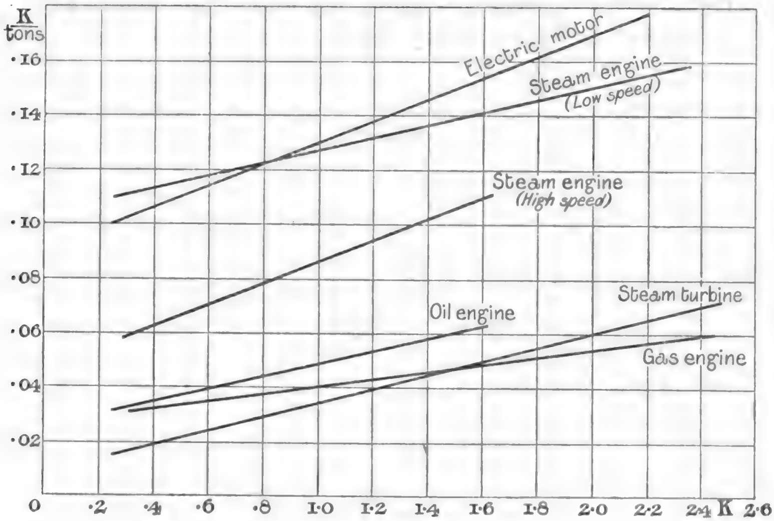


FIG. 3.

course be obtained in such a comparison, and very many instances of individual motors occur the weight of which differs very materially

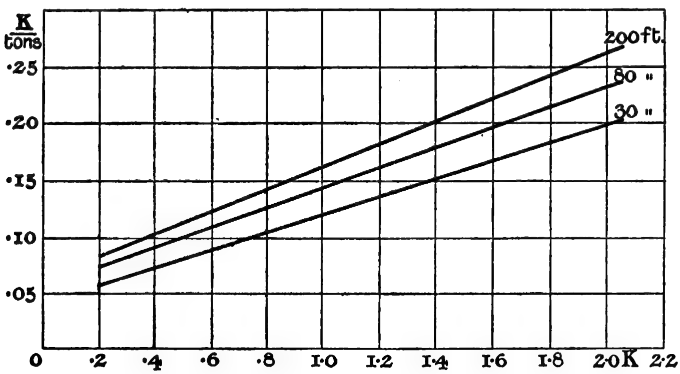


FIG. 4.

from that indicated by the average line for their type. Especially is this the case with engines made singly and not manufactured as one of a line of similar motors. Some general engineers, for instance,

manufacture (as one part only of their business) steam engines for various purposes, and their weights are extremely erratic, often varying by 100 per cent. or more from those indicated by the mean line of steam-engine weights. The figures are only intended to show the average results obtained on one type of motor as compared with what has hitherto been obtained on other types.

TABLE SHOWING THE HORSE POWER PER REVOLUTION OBTAINED IN DIFFERENT TYPES OF MOTORS FOR 1 TON OF MATERIAL.

K.	Steam Engine		Gas Engine.	Oil Engine.	Steam Turbine.	Electric Motor.	Water 30 ft. Head.	Turbines 80 ft. Head.	200 ft. Head.
	Low Speed.	High Speed.							
0·02	0·097	0·048	0·033	0·021	—	0·023	—	—	—
0·10	0·099	0·052	0·034	0·027	0·014	0·057	—	—	—
0·20	0·110	0·056	0·036	0·032	0·017	0·082	0·055	0·075	0·081
1·00	0·130	0·086	0·040	0·048	0·034	0·130	0·120	0·140	0·160
2·00	0·150	—	0·054	—	0·060	0·170	0·195	0·230	0·260

Considering the results in detail, it appears from Fig. 3 and Fig. 4 that the water turbine gets the largest horse-power per revolution per unit weight of all the motors considered, the figures varying from about 0·07 H.P. per revolution per ton weight when K = 0·2 up to 0·23 H.P. per revolution per ton when K = 2·0. Next to the water turbine the electric motor, when of a fairly large output, has the highest weight efficiency of any of the types considered. The horse-power per revolution to be obtained from one ton of material varies between 0·082 of a horse-power when K = 0·2 up to 0·17 of a horse-power when K = 2·0. Or if it be preferred to avoid fractional figures, the electric motor of sizes varying between the limits indicated would give at 1,000 revolutions (were such speed possible) 82 up to 170 B.H.P. for each ton of material used in the machine.

At a value of K of about 0·2 the slope of the curve for the electric motor appears to decrease somewhat suddenly, the values of output per ton below this value of K falling away rapidly as the machine becomes smaller; at K = 0·05 there appears to be another rather sudden change, indicated in Fig. 2. The examination of several different makers' recorded weights and output gives the same result of a sudden change in the slope of the curve and agrees in giving that change in the neighbourhood of K = 0·05. I might add here that this sudden change seemed so remarkable that I spent a considerable amount of time investigating it. At first my only conclusion was that the straight line did not really represent the electric motor. A great many

makers' figures which I got indicated a comparatively sudden change as occurring at just about the same points. As the change was quite sudden and did not indicate that the actual facts would be shown any better by means of a curve, I kept the straight line hypothesis, and showed a straight line for the electric motor with two breaks indicated on Fig. 2, and by the change of slope between Fig. 2 and Fig. 3. No such sudden change was indicated on the figures I had access to for any of the other types of motor considered.

Of the other types investigated, the slow-speed steam engine is the one from which the highest horse-power per revolution is obtained from 1 ton of material. The horse-power per revolution for 1 ton weight varies between 0·1 of a horse-power in engines having a value of $K = 0{\cdot}25$ up to 0·16 of a horse-power in engines having a value of $K = 2{\cdot}5$. These figures relate to engines commonly described as slow-speed engines. For the high-speed totally enclosed engines of the type commonly used for direct coupling to generator the figures are distinctly lower: the horse-power per revolution obtained from these for 1 ton of material used varies from 0·06 of a horse-power per ton when $K = 0{\cdot}25$ up to 0·105 when $K = 1{\cdot}5$. These figures are for engines working with about 180 to 200 lbs. steam pressure. Oil engines and gas engines appear to be very similar as regards output for a given weight, and give about 0·035 H.P. per revolution for 1 ton weight when $K = 0{\cdot}25$, increasing to 0·05 H.P. per revolution for 1 ton when $K = 1{\cdot}5$. Steam turbines working at about 180 to 200 lbs. steam pressure are lower in their output for the smaller sizes than either gas or oil engines, but in the larger sizes the curve of output rises above that of the gas or oil motor; the figures for the steam turbine being 0·02 B.H.P. per revolution for 1 ton weight when $K = 0{\cdot}25$ and 0·075 B.H.P. per revolution for 1 ton when $K = 2{\cdot}5$.

The consideration of the water turbine differs somewhat from that of other motors, in that the power of the same turbine varies with the head at which it works; it is, of course, true that in the same way the power of the steam engine varies with the steam pressure, but the steam pressure can usually be chosen for any installation and is under the control of the designer; the head at which a turbine shall work is, on the contrary, rigidly fixed. As, however, the speed of the turbine, as well as its power, depends on the head, the results of comparing the weights of turbines working at different heads are not so variable as might at first sight have been imagined. Curves of horse-power per revolution given out for each ton weight have been plotted for water turbines working at 30 ft., 80 ft., and 200 ft. head (Fig. 4).

The comparison of results in Figs. 2, 3, and 4 raises the questions as to why the manufacturer of electric motors, of water turbines, and of steam engines is able to get so much more output out of a ton of material than is obtainable in a gas or oil engine, and whether these different results are entirely and essentially of the nature of the case, and therefore unavoidable. It is not proposed to discuss these questions here, but merely to put before you the results as they appear to emerge

from an investigation of those particular figures to which I have had access.

In addition to considering merely the broad lines of comparison between different types of motors, many points of interest arise in individual cases. To mention one only, the very highest output per revolution per unit weight of material was found in two instances of a very widely varying nature, one case being that of a petrol engine manufactured for aeroplane work, in which as much as 0·4 H.P. per revolution is obtained from 1 ton of material. It was, of course, to be expected that in an engine built for such a purpose, where lightness is the one essential quality to be sought for, a very high weight of efficiency would be found. This high efficiency is in this case obtained by sacrificing durability. I understand that the standard aimed at in such an engine is that it should run at full load for 100 hours before requiring a thorough overhaul; if it fails to reach this standard it is deemed too flimsy for its work—the light weight has been obtained at too high a sacrifice.

The other case of very high output for weight is found in a very different class of machine. A slow-speed colliery winding engine is rated by the makers at brake horse-power which works out to 0·5 H.P. per revolution for each ton of material used. In this case, of course, weight is of comparatively little importance, and it is not by any systematic effort to reduce weight that the above result is obtained, but by a very high rating of the power, which is only required intermittently, and by sacrificing the fuel economy, the steam being admitted at full pressure throughout the stroke. It is interesting, however, to find two engines practically at opposite ends of the scale, and made for such totally distinct purposes, both coming out so high in the matter of weight efficiency, and to note by what very different processes this result is attained.

The lowest weight efficiencies naturally occur in cases where K is very low; there are on the market electric motors and water motors, to take only two instances, so small as to be toys rather than engineering apparatus, and in all these very small machines the weight efficiency is necessarily low. The lowest figure actually met with was 0·0068 H.P. per revolution for 1 ton of material; that is, this particular motor, if it could have been increased proportionately to weigh 1 ton, would at 1,000 revolutions have given only 7·8 H.P., or only about $\frac{1}{75}$ part of the highest output met with, namely, 0·5 H.P. per revolution per ton.

Discussion.

Mr. Murray.

Mr. T. Blackwood Murray: For the engineer it is not a very useful basis of comparison of weights to consider horse-power per revolution, and it brings out some curious results. If I did not know that the author was an electrical engineer, I would be led to the conclusion he was a maker of colliery engines and hauling gear. His

paper gives us the impression that he holds a brief for that class of prime mover. What engineers are out for is to get the highest horse-power output per ton of plant. In the slow-speed engine the engineer is not in any way penalised. He has no centrifugal stresses to consider, no inertia stresses to speak of, and no difficult questions of balancing to deal with; whereas in high-speed internal combustion engines the driving forces are very irregular, the inertia stresses are enormous, in some cases several times as great as the highest stresses due to the explosive forces. I do not think it is difficult to see why the ordinary slow-speed gas engine should come out rather poorly in the author's scale of comparison. It is a much more difficult problem than the design of an electric motor or steam engine, where the torque is fairly constant. The gas engine has a very high impulsive force at one period of its stroke, and as the whole engine has to be designed to carry these very high stresses the weight must necessarily be high per horse-power per revolution per ton. On page 622 Mr. Hird says that if the horse-power is constant the torque will remain the same and the strength of the parts must be constant. But while that is approximately true with respect to electric motors and for the steam turbine, it is far from being true with reference to reciprocating engines. The inertia stresses become very serious at high speeds in such engines. The author's figures, no doubt, have an academic interest generally, or may certainly be useful in comparing strictly similar machines; but I think the basis of comparison of true interest to the engineer should be "output per ton." I do not like to let the author's record for the colliery engine remain unchallenged. I see that the latest E.N.V. aeroplane engine works out at 0·85 H.P. per revolution per ton, which is rather better than that of the colliery engine. **Mr. Murray.**

Mr. G. STEVENSON: The first thing I would like to refer to is the sentence on page 621: "The size and therefore weight of an engine or motor naturally increases with the power at which it is rated, but it decreases with the speed at which this power, this rate of giving out energy, is obtained." I am obliged to say that I do not quite follow that. Perhaps the author will refer to it in his reply. His statement means that as the speed decreases the size would decrease—which, of course, is obviously wrong. With regard to the curve showing the case of electric motors (Fig. 2), it would be interesting to know whether the motors were direct-current machines or 3-phase. I think 3-phase machines would come out differently. Then with regard to the steam turbine, I must confess it was rather a surprise to me to find that it was in such a poor relative position as compared with the slow-speed engine. Perhaps the author will amplify his remarks in regard to it. I do not know whether he has included condensing plant. [Mr. HIRD: No, condensing plant is not included.] It is all the more surprising to find the turbines with such a low efficiency. **Mr. Stevenson.**

Mr. MCWHIRTER: The author's results are very interesting, but what appears to me of most importance is the enormous change that has taken place in electric motors during the last twelve years. If we **Mr. McWhirter.**

Mr. McWhirter. go back a little further and, instead of motors, take dynamos, which were then more common, the change which has taken place in weight and efficiency is exceedingly great. I think one factor that accounts in a large measure for the low efficiency of the gas engine, and one that we must all have before us, is the fact that there is only one impulse for four movements of the piston, whereas in the steam engine there is an impulse each stroke. As Mr. Murray says, the parts have to be made very heavy to enable them to withstand the enormous stresses made by the gas explosions.

Mr. Foyster. Mr. A. H. FOYSTER: Fig. 2 seems to me to show what we should expect to find. At first glance it would appear that the low-speed engine comes out best because its designers have had a longer experience and have been able to cut down their designs to the highest weight efficiency, whereas the designers of gas and oil engines have not yet reached finality. But, considering the matter further, I am inclined to think it is more a question of price. The designers of high-speed machinery can afford to allow a higher factor of safety because they are getting so much more power for a given weight. What we want to know about any class of machinery is not so much whether the total weight is correct as whether the weight of each part agrees with that of other manufacturers. The total weight might be all right, but this total may be made up of certain parts which are much too light, balanced by extra weight in a part where it is not necessary. The author has put a great deal of work into his paper, but if he would go still further into the question and compare the weights of the different parts of any class of machinery he would give us much more valuable information than he has given us to-night.

Mr. Mavor. Mr. SAM MAVOR: I am quite sure that not the least part of the labour of preparing this paper must have been in accumulating the data for it, and I think that if the members, who are in a position to do so, would send such data as the last speaker has suggested, Mr. Hird would be very pleased to tabulate it. The paper brings out several paradoxical and surprising points. For instance, the last page shows that an aeroplane engine and a slow-speed colliery engine are together at the top of the list. The colliery winding engine is in a class by itself, because it, as we know, carries high-pressure steam practically during the whole length of its stroke. It is very curious that two engines so different in type and purpose should be so closely associated on the author's curves. There is a great deal in what the last speaker has said with regard to the weights of respective parts of motors of different designs. Some which approximately follow the same general line may be essentially different in respect of detail of design. In this country I think we have been behind in machine design, and especially machine-tool design, in having unprofitable distribution of weight. No doubt our pre-eminence was built up by strength and solidity, but that was carried to an unprofitable extreme. Beyond any doubt the same criticism was, until recently, applicable to electric motors designed in this country, especially of the 3-phase type. The total weights of

our motors were very much greater than some of the best-designed continental machines, and the extra weight in our machines was not so distributed as to justify itself. The improvement in weight efficiency of electric motors of moderate size in this country has been immense; so much so that a few years ago it was not at all unusual for a manufacturer to supply a new motor in exchange for an old one: the cost of the new motor being less than the scrap value of the old one. I had quite an interesting example of the difference in weights a few days ago; I had been using a number of gun-metal valves by a well-known English maker, but saw valves in America which struck me as being very well designed. I compared one of the American valves for a similar purpose with the English valve, and found the weight to be considerably less than one-half. The American valve is quite as good a valve for all ordinary purposes; such extravagance of material is still characteristic of a great deal of our manufacturing in this country. There is still room for improvement, and the line of investigation that Mr. Hird has pursued is very suggestive and practically useful when developed and applied. Mr. Mavor.

Mr. E. P. Hollis (*communicated*): The problem which the author has attacked in his paper is one which is of great interest to every designer. Every one, of course, desires to get the best out of his material, but the investigation which the author set out to conduct is one which bristles with difficulties. The enormous ranges of speed make comparisons difficult enough between prime movers of the same type; between prime movers of different types comparisons are, I think, impossible. I will assume for the moment that it is possible to obtain figures representing the "weight efficiency" of, say, a steam engine and an oil engine. But of what use are they? Will they enable us to decide upon what form of drive to adopt? Obviously not, for such little items as boilers, condensers, and so forth, are omitted in the case of the steam engine, while the oil engine is a self-contained power unit. No comparison is possible on such a basis. Again, does "weight efficiency" offer a criterion of good design, or act as an incentive to the designer? Any such contention will get short shrift when we consider the weight efficiency of the aeroplane engine (0·4 H.P. per rev. per minute per ton) and the colliery "steam eater" (0·5 H.P. per rev. per minute per ton), the latter having a higher weight efficiency than the most modern machine the author has investigated. Is "weight efficiency" a criterion of cost? How can it be? Even if the weight of metal irrespective of the speed were involved in the formula labour is left out of account, and it is that which costs money. If weight efficiency were a criterion of cost, then according to the author's graphs the steam turbine ought to cost over three times as much per horse-power as a slow-speed reciprocating engine. Parenthetically I am tempted to inquire by what process of reasoning the author gives the result of his calculation the name "weight efficiency." He divides horse-power by weight and by speed, and calls the resulting product "weight" efficiency. But surely it is just as much "speed" efficiency Mr. Hollis.

Mr. Hollis. as "weight" efficiency. As a matter of fact it is neither. Let us examine the matter:—

$$\text{Weight efficiency} = \frac{\text{horse-power}}{\text{weight} \times \text{speed}}$$
$$= \frac{\text{constants} \times \text{torque} \times \text{speed}}{\text{weight} \times \text{speed}}$$
$$= \frac{\text{constants} \times \text{torque}}{\text{weight}}.$$

So that as a matter of fact the figures in the author's tables express "torque efficiency."

Mr. Hird. Mr. W. B. Hird (*in reply*): I think that the object I put before myself in writing this paper has been very well realised in the discussion raised. I wished to attract attention, to a certain extent, not only to the question of weight efficiency, which is the object of the paper, but to the fact that such comparisons could be made with good results in various other lines of engineering subjects. Confining myself more strictly to the question of weight, and taking in order the individual criticisms which have been made, I would say, first, in reference to Mr. Stevenson, that I have to thank him for his correction. The sentence to which he referred reads all right, but, on his drawing attention to it, I see that it says exactly the opposite of what I meant to say. The weight, of course, decreases with the increase of speed. I am sorry to take away any credit Mr. Stevenson might claim for an original suggestion, but I really did think of including windmills. I did not, however, find enough figures of weights to make it possible to include these.

With regard to Mr. Blackwood Murray's remarks, I would like to point out that I have been very careful not to hint that I attached any special merit to the man who got his curve above all the others. Of course, it is quite natural for those engaged with high-speed engines to consider the line of comparison as not quite a fair one. The man who makes the lightest engine and gets the biggest horse-power out of a certain weight, even at increased speed, certainly deserves the credit of getting the biggest horse-power out of a given weight of material, and of overcoming all the difficulties incident on high speeds. But I wished to make a comparison between all types of prime movers, and therefore had to take some other basis of comparison; it would obviously be ludicrous to undertake a comparison of horse-power per unit-weight between, say, a slow-speed winding engine and a modern high-speed engine. Some of the points raised by Mr. E. P. Hollis are similar to Mr. Murray's criticisms, and are partly answered above. The horse-power per revolution given out by an electric motor is so commonly used as an indication of the size of the machine, that it is difficult to understand the objection raised to its use as a basis of comparisons. The same motor carcases can be wound to give, say, 10 H.P. at 600 revs. per minute and about 13 H.P. at 1,000

revs. per minute; the weights in both cases will be approximately the same. In the same way an examination of catalogues published by manufacturers of steam engines, of water turbines, etc., show that they frequently rate the same machine at different horse-powers by proportionately varying the speed. The horse-power divided by the revs. per minute is in each of these cases a distinct property of the individual machine, and remains approximately the same for that machine over the whole range of speed of which it is capable; if we pass beyond that range of speed, a different machine has to be designed and an entirely new set of conditions dealt with, and what I have called the weight efficiency is altered: it is the direction of this alteration that I have tried to investigate. Mr. Hird.

Mr. Hollis is quite correct in pointing out that the relation dealt with is between torque and weight, but it is not clear why he wishes this relation to be called torque-efficiency rather than weight-efficiency; the term was chosen as being a simple one to express the relation and was used in a way which is quite common at any rate in dynamo and electric motor design. As to the usefulness of the comparison, Mr. Hollis appears to take a somewhat narrow view of the subject. Of course there is no suggestion that cost bears any simple relation to weight efficiency, nor is the relation between good design and weight efficiency a simple one. I have entered no claim of highly superior design for the manufacturer of the colliery "steam-eater," but I think that he might quite reasonably object to Mr. Hollis's imputation that his design is necessarily inferior and on an altogether lower level than that of the manufacturer of the modern aeroplane engine. Each of them is successfully solving the problem put before him, and in proportion to their success so do they deserve credit for their design. Between prime movers of the same type a simple comparison of weight efficiency and of other properties may be directly useful in deciding between the products of different manufacturers; if we compare different types, such a crude comparison is of course useless, and any practical results which may be obtained must be looked for further below the surface. The contention is that our general knowledge of engineering matters may be considerably increased by such comparison, and that this increased general knowledge may affect various points of design.

In answer to Mr. McWhirter, I might mention that when I started to get these figures together I had intended to include a comparison between results obtained twenty to thirty years ago and results obtained now, but I unfortunately found it impossible to get sufficient figures to give any hope of attaining a safe basis of comparison, even with electric motors. The figures were not sufficient to make me feel I had any firm basis to go upon. I had to drop everything except present-day results.

It has also been proposed that a comparison should be made between parts. That is just the sort of investigation I should be anxious to see started. The obtaining of the required information would, however,

Mr. Hird. be a most difficult matter. The determining reason which caused me to choose the particular line of investigation out of the large number which might have been selected was that the information required was comparatively easily obtained. It only meant the labour of asking for it and of tabulating it when obtained. This also refers to some remarks made by Mr. Mavor. Such a comparison would be most interesting when carried out for different parts and details as well as for the machine as a whole.

INDUCTION MOTOR DESIGN.

By J. K. CATTERSON-SMITH, Associate Member.

(*Paper received* 31*st May*, 1912.)

PART I.—A NEW INDUCTION MOTOR TEST.
PART II.—STARTING TORQUE PHENOMENA.
PART III.—TORQUE AND SLIP RELATIONS.

PART I.—A NEW INDUCTION MOTOR TEST.

The author presents this short paper for two reasons: firstly, because it deals with a few points in connection with the circle diagram to which as far as he is aware allusion has not been made previously, and, secondly, because in common with others he has noticed in many instances the difficulty that students have in grasping the simple idea of representing the mechanical output of an induction motor by the loss of energy occurring in a fictitious non-inductive resistance inserted in the rotor or secondary circuits at a standstill. This conception, as is well known, leads to a very simple deduction of the circle diagram from general transformer principles applied to the treatment of the motor, and one which is quite straightforward provided the physical meaning of the above representation is realised. It is in connection with this that the author has set out the following notes, which he trusts may, apart from the interest of the experimental method, prove of a little service to others in carrying out tests for practical purposes.

Description of Test.—The diameter of the circle is given by the applied pressure divided by the sum of the stator and rotor reactances* [$E \div p(L_1 + L_2)$] and is independent of the resistance of the stator or rotor circuits; on the other hand, the position of the short-circuit or standstill point on the semicircle is determined entirely by the stator or rotor resistance and, as is therefore obvious, short-circuit points may be located anywhere on the semicircle by the insertion of suitable non-inductive resistances in either the stator or rotor circuits when testing a motor on short circuit.

* See Appendix.

It is advantageous to insert the resistance in the rotor circuit whenever possible, because there is a certain value of rotor circuit resistance which will carry normal current when the full line voltage is applied, and under these conditions both the main and leakage fields have normal working values, whereas in the short-circuit test as usually carried out the main field is greatly reduced, and hence the machine is not operating under normal magnetic conditions. Exactly the same drawback exists if extra resistance is inserted in the stator circuit as the author proposes for this test, and therefore the resistance should be placed in the rotor circuit whenever possible. This may be carried out on any motor which is fitted with slip-rings, but all short-circuited or squirrel-cage motors must be tested with the extra resistance provided on the primary side.

Referring to the ordinary simple circle diagram shown in Fig. 1, the point P obtained in the usual manner from the short-circuit obser-

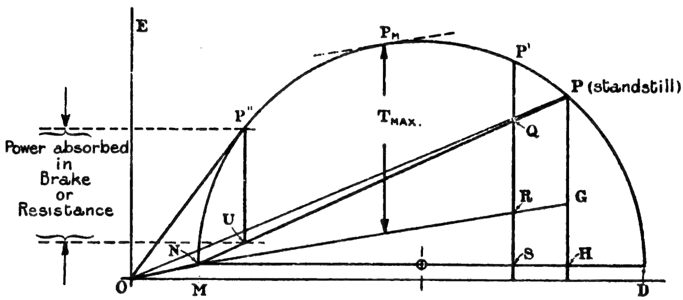


FIG. 1.

vations gives the total copper loss in the windings P H, made up of G H, the stator copper loss, and P G, the rotor copper loss. The starting torque under these conditions is measured by P G, and may be increased by the insertion of external or starting resistance in the rotor circuit, which simply causes P to move along the arc to a new point such as P′ on the circle. The starting torque is now P′ R measured to the same scale as before,* and the I^2R losses are primary R S, secondary Q R internal and P′ Q external (in starting resistance). The torque may be increased to a maximum value at P_m, after which it is evident that further increase in the external resistance will give other points on the circle such as P″, having reduced torque and correspondingly increased power factor.

* If the length P′ R is measured to the watt scale then—

$$\text{Torque in lb.-ft.} = \frac{\frac{33{,}000}{746} \times \text{rotor watts input}}{2\,\pi \times \text{synchronous revs. per minute}}.$$

Thus a point on the circle P″ may be obtained in two ways :—

1. *Motor at a standstill* with an external non-inductive resistance (starting resistance) inserted in the rotor circuits having a loss equal to P″ U watts, or
2. *Motor running* on a brake load of P″ U watts.

Thus the horse-power of an induction motor may be represented accurately by the loss taking place in a fictitious non-inductive resistance in the secondary circuit with the motor at a standstill.

Any point lying on the circle between short circuit (P, with no external resistance) and no load (N, with infinite external resistance)

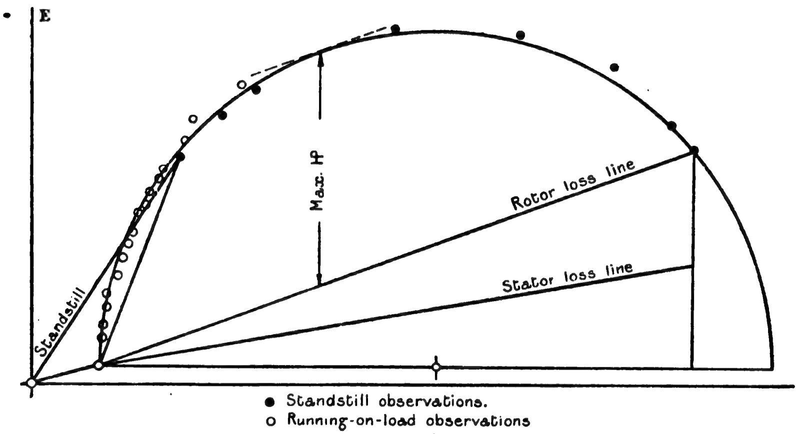


FIG. 2.

may be obtained by simply adjusting the value of the external non-inductive resistance inserted in the secondary circuit.

The results of some experiments made by the author in confirmation of this method are given below, and it will be seen that the test affords a new experimental method of arriving at the circle diagram and also a clear insight into the relative behaviour of a motor under running and standstill conditions, which has been found of considerable value for teaching purposes.

For the sake of completeness it is convenient to add in an appendix the deduction of the circle diagram from transformer principles by means of equivalent circuits as given in text-books on this subject.

It may be noted that in carrying out the short-circuit tests it is often possible to utilise the ordinary starting resistance belonging to the motor,* provided it is liberally rated and is practically non-inductive.

* Thus avoiding the necessity for any special gear for the test described in the case of small motors.

Experimental Confirmation of Method.—Two tests on small motors at the University of Liverpool are quoted below, the external resistance in both cases being an eight-stud starter kept cool by an air-blast from a small fan.

TABLE I.

No. of Test.	I.	II.
Results shown in	Fig. 2	Fig. 3
Motor rating	10 H.P.	5 H.P.
Number of phases, stator	3	2
Number of phases, rotor	3	3
Stator voltage	200	200
Frequency	50 ∿	50 ∿
Number of poles	4	4
Short-circuit points thus (standstill) ...	●	●
Running on load	o	o

Utility of the Method for the Test-plate.—In dealing with tests required for checking the design of induction motors, particularly new lines, there is often considerable difficulty in determining the diameter of the circle in consequence of the uncertainty which must

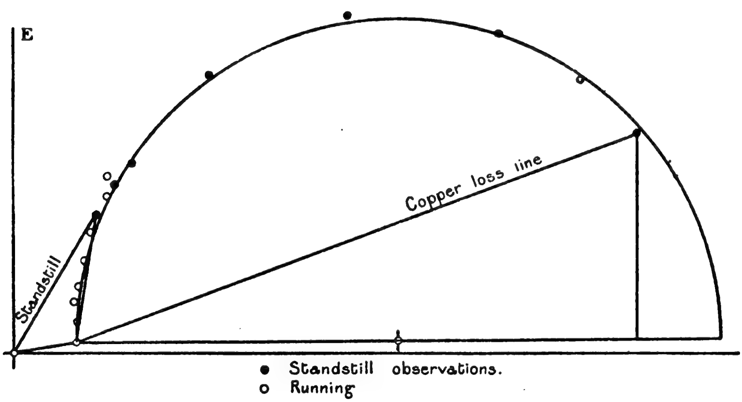


FIG. 3.

always exist to some extent as to the value of the current at short circuit.

The plan commonly adopted in making this observation of allowing the rotor to slip * round slowly while the pressure applied to the stator

* Some prefer to rotate the rotor slowly *against* its direction of rotation whilst making the observation.

is reduced until the short-circuit current has a value approximating to the full-load current of the motor, and thus producing normal values of ampere-turns per slot, has the disadvantage that everything depends upon this single reading, and therefore it appears to the author that the plan he proposes of taking *several short-circuit* readings has much to recommend it for practical testing, especially when it is remembered that the short-circuit points corresponding to the running side of the diagram may be obtained with normal line voltage on the motor, and hence *without reduction of flux density* in gap or teeth.

Application to Squirrel-cage Motors.—As pointed out early in the paper, the extra resistance for short-circuit tests on short-circuited rotors can be inserted only in the stator circuit, and will cause the point P (short-circuit) Fig. 4 to move round to P′, but *without* increase of torque, for the point G now moves to G′, and the starting torque

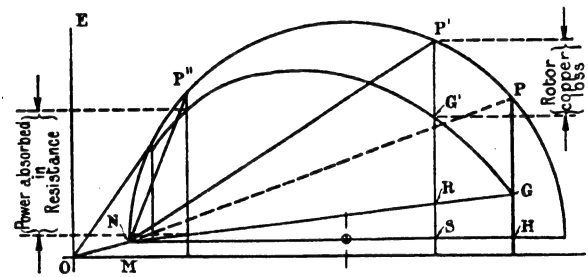


FIG. 4.

P′ G′ is *less* than P G. The stator copper loss is R S, and the loss in the additional resistance is G′ R, which represents the power output of the motor in the same way as P′ Q in Fig. 1. Thus short-circuit points lying anywhere between P and N on the arc may be obtained in this simple manner for squirrel-cage machines, and with the same flux densities throughout the whole range as would exist in the determination of the single short-circuit reading ordinarily observed.

PART II.—STARTING TORQUE PHENOMENA.

As is well known, induction motors fitted with squirrel-cage rotors will sometimes fail to run up to full speed; that is to say, the motor accelerates up to a certain point, and then runs steadily at that speed. This phenomenon has been noticed chiefly in connection with—

1. Induction motors in which the windings are not sufficiently distributed.
2. Induction motors in which the number of poles is changed for speed control purposes, and
3. Synchronous motors and rotaries which are run up by means of the action of a squirrel cage embedded in the poles.

In the case of 3-phase machines the speed at which this phenomenon of "crawling" takes place is commonly one-seventh of synchronous speed; the author has never observed a commercial 3-phase motor to "crawl" at any other fraction of its synchronous speed.

The cause is, of course, the presence of ripples on the rotating flux wave; these ripples rotating at various speeds which are fractions of synchronous speed.

In a recent paper Mr. C. F. Smith * discusses the variations in flux in detail, and upon this the author will not dwell, but he desires to draw attention to one or two points in this direction apart from the effects of want of uniformity of the gap, cogging, etc., which are of considerable importance in designing squirrel cages.

Considering the field produced by each phase, it is clear that the only parts which can add to produce a wave of constant value and uniform velocity are the sinusoidal components of each wave, the fundamentals adding together to produce the main synchronous field and all harmonics of a given wave-length add and produce waves of constant value, but rotating at speeds other than that of the main fundamental wave.

The simplest case is that in which each phase produces a wave having a simple sine time-variation, but in which the space distribution is not a sine law owing to the position of the coils in the slots on the stator.

In the case of a 3-phase machine there will be, in addition to the main synchronous flux, other flux waves, one rotating backwards at one-fifth † synchronous speed, another rotating forwards at one-seventh synchronous speed, etc. These fields which are superimposed upon the main field do not cause trouble when the motor is running near synchronism, because the eddy currents they produce in the low-resistance rotor circuits are almost out of phase with these fields, and therefore produce little or no torque. When, however, the motor is accelerating from rest, they may have pronounced effects, especially in the case of a squirrel-cage motor in which the starting torque cannot be increased by the insertion of starting resistances.

Some idea of the magnitude of these harmonic fields may be gathered from the following table (Table II.), which gives the amplitudes of the component relative to the original wave in the extreme cases of a winding for 3 phases concentrated in a single slot per pole per phase, and a winding uniformly distributed over one-third of the pole-pitch.

Thus, in the case of a 3-phase winding, the flux wave rotating at one-seventh full speed has an amplitude as much as 18 per cent. of the main wave when a concentrated winding is employed, or only 2 per cent. when a uniformly distributed winding is used.

* "The Irregularities in the Rotating Field of the Polyphase Induction Motor," C. F. Smith. *Journal of the Institution of Electrical Engineers*, vol. 46, p. 132, 1910.

† All harmonics having a frequency with regard to space of 3, or any multiple of 3, times the fundamental cancel in the 3-phase case. The fifth harmonic has five poles in the space of one main pole-pitch, and when added to the other phases it glides slowly backwards.

During acceleration the rotor is influenced by all the rotating fields, the effect of any one particular wave depending on the speed attained by the rotor. Thus the initial torque of a 3-phase motor is made up of the torques due to the main field and seventh harmonic in a positive direction and negative torque due to the fifth and eleventh harmonic fields.

When a speed of nearly one-seventh full speed is reached the rotor receives maximum torque due to the seventh harmonic, which then falls to zero at exactly one-seventh full speed. Above this speed the main torque is opposed by the torque of the fifth and seventh harmonics,

TABLE II.

Components of M.M.F. Waves.			
	Winding Distribution.		
	Rectangular.	Uniform over ⅓ Pole-pitch.	Half-pitch, as in Fig. 7.
Fundamental	1·270	1·220	0·895
3rd harmonic	0·423	0·281	0·295
5th „	0·254	0·055	0·170
7th „	0·181	0·024	0·091
9th „	0·141	—	0·049
11th „	0·115	—	0·015
Amplitude of any component is $y = a \times$ above factor, where $a =$ amplitude of original wave.			

and if the sum happens to be less than the friction and load against the motor it will fail to accelerate further, and will continue to "crawl" at this speed.

When a motor crawls it is running practically on short circuit with regard to the fundamental wave, and will rapidly overheat.

The above effects are illustrated by Fig. 5, in which the torque curves for the fundamental, fifth and seventh harmonics are drawn, and also their sum, showing the variation of torque due to the seventh harmonic. Should the torque at this point fall below the friction torque the motor will not run past the point marked C.

The condition of stability in the running of the motor is that with a given load torque the torque produced by the rotor must increase with

any drop in speed. This condition is met by the part of the curve lying between synchronous speed and the vertex; with the exception of the stable part at one-seventh synchronous speed all the rest of the curve represents unstable conditions, and the motor will not run on these parts in ordinary cases; an exception might occur in the case of an induction motor coupled to a fan, where the variation of torque required by the fan might allow the motor to run steadily on the otherwise unstable parts of the curve, but even in this case the system would be very sensitive.

The following instances of the crawling of a squirrel-cage rotor recently observed are thought by the author to be of interest and may

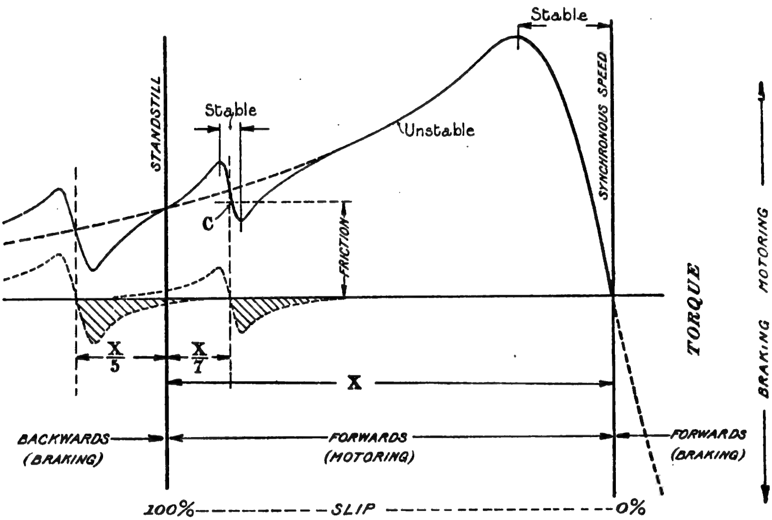


FIG. 5.

be recorded. A 10-H.P. 3-phase 4-pole motor built by Messrs Crompton for the University of Liverpool and arranged to run either at 1,500 revs. per minute with 4 poles, or at 3,000 revs. per minute with 2 poles, has two stator coils per phase as shown in Fig. 6. This gives a very irregular M.M.F. wave when the machine is changed over to 2 poles (Fig. 7), and the consequence is that the machine will not run up to full speed as a 2-pole motor even when unloaded, but sticks or crawls at about 430 revs. per minute. In this case full speed can only be reached by first accelerating with 4 poles to above 430 revs. per minute and then changing over to 2 poles.

Further, when this motor with 2 poles is connected in cascade with a 4-pole 50-cycle motor the combination should run at $\frac{120 \times 50}{(4+2)} = 1{,}000$

revs. per minute, whereas it actually crawls at about 330 revs. per minute, *i.e.*, the auxiliary motor tends to run at the speed of its seventh harmonic, or as a 14-pole motor, so that the combination speed is $\frac{120 \times 50}{(14+4)}$ or that of an 18-pole motor. It is therefore clear that this form of pole changing is not always suitable for induction motors, and

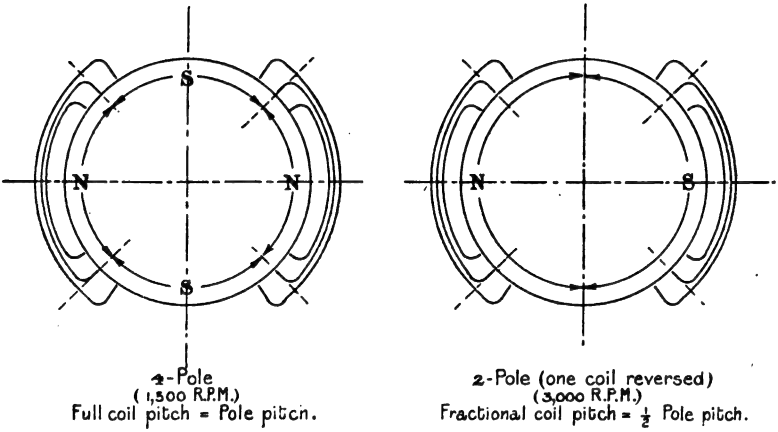


FIG. 6.

in the author's opinion some better distribution of windings should be employed for changing the number of poles.

In the case of synchronous machinery which is "run up" by means

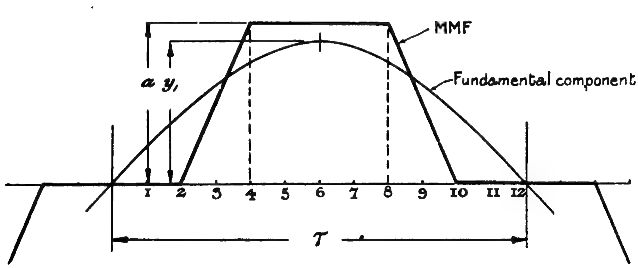


FIG. 7.

of a squirrel cage in the pole-faces, a very irregular flux wave is produced owing to the presence of the salient poles and interpole spaces, and for this reason one sometimes hears of the failure of such an arrangement to bring the machine into synchronism.

Two ways of avoiding these troubles suggest themselves at once:—

1. By arranging the resistance of the squirrel-cage rotor to be of sufficient value to meet any likely reduction of torque due to the harmonics; this reduction rarely exceeds 30 per cent., and so by allowing for this at starting, and for the increase in the negative torque due to the additional resistance in the rotor, it is possible to arrive at a safe value of rotor resistance.
2. It is plain that the harmonic flux can only produce rotor currents, and hence torque, in the case of rotors having a sufficient number of phases or wound with a sufficiently distributed winding to respond to these flux waves of small pitch. This is the reason why only squirrel-cage motors exhibit the phenomenon to any extent. Thus by selecting the pitch of the bars of the squirrel cage such that they cannot link inductively with the harmonic flux the danger of negative torque will be avoided. A 3-phase machine with a pole-pitch of 50 cms. has a wave-length of $\frac{100}{7} = 14{\cdot}3$ cms. for the seventh harmonic flux wave, and thus if the pitch of the bars in the pole-faces was made equal to 14·3 cms. they could never link the flux inductively. On the other hand, there are certain objections to the small number of rotor bars that results from this arrangement which could only be met by the provision of *two separate* cages in the form of a double winding. This method is shown diagrammatically in Fig. 8, where each squirrel cage is non-inductive to the seventh harmonic; at this speed the negative torque due to the fifth harmonic is negligible.

Part III.—Torque and Slip Relations.

Some of the most useful relations for design purposes which the circle diagram makes evident are those between *torque* and *slip*, which may be derived in the following manner:–

Let the torque be measured by the ordinates between the horizontal diameter and the arc in Fig. 9; in other words, let the stator copper loss be ignored so that—

$$\frac{T}{AD} = \frac{S}{S_m} \text{ or } AD = T \times \frac{S_m}{S} \text{ for } MD = S_m,$$

and—

$$\frac{MA}{T} = \frac{S}{S_m} \text{ or } MA = T \times \frac{S}{S_m},$$

also—

$$MD = MA + AD = T\left\{\frac{S}{S_m} + \frac{S_m}{S}\right\};$$

further—

$$T_{\text{max.}} = \tfrac{1}{2} M D,$$

therefore—

$$\frac{T}{T_{\text{max.}}} = \frac{2}{\frac{S}{S_m} + \frac{S_m}{S}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where—

$$S = \text{slip at any torque } T$$

and—

$$S_m = \text{slip at maximum torque } T_{\text{max.}}.$$

If equation (1) be rewritten for the particular case of starting, when $S = 1{\cdot}0$ it becomes—

$$\frac{T_{\text{start.}}}{T_{\text{max.}}} = \frac{2}{\frac{1}{S_m} + S_m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The utility of these two equations is fairly obvious, and the author takes this opportunity of expressing his appreciation and acknowledgment of the writing on this subject by Dr. Max Kloss,* who, he believes, first drew attention to these equations for the ratios of torque and slip in squirrel-cage motors.

As illustrative of the application of these equations two examples may be considered :—

1. What would be the slip at full load and at maximum torque in the case of a squirrel-cage motor designed for an overload torque capacity of 150 per cent. and 20 per cent. margin with a starting torque of 125 per cent. of full-load torque?

Here—

$$\frac{T}{T_{\text{max.}}} = 0{\cdot}40 \times 0{\cdot}80 = 0{\cdot}32,$$

and—

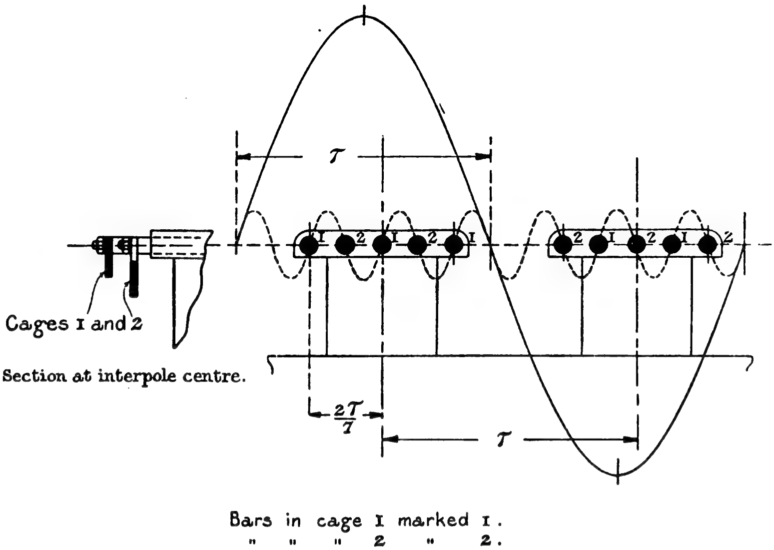
$$\frac{T_{\text{start.}}}{T_{\text{max.}}} = 1{\cdot}25 \times 0{\cdot}32 = 0{\cdot}40,$$

from which—

Equation (1) gives $S_m = 21$ per cent., and
Equation (2) gives $S \;\; = 3{\cdot}68$ per cent.

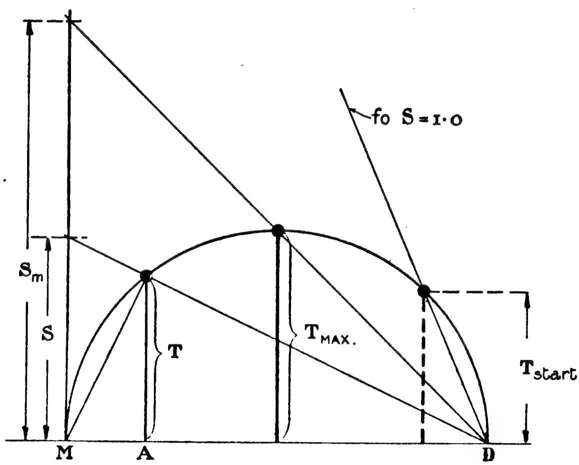
2. What starting torque may be obtained from a squirrel-cage motor rated at 100 per cent. overload torque capacity and a slip of $2\frac{1}{2}$ per cent. at full load?

* "Starting Torque of Three-phase Motors," M. Kloss, the *Electron*, vol. 2, p. 18, 1909.



Cages 1 and 2
Section at interpole centre.
τ
2τ/7
Bars in cage 1 marked 1.
" " " 2 " 2.

FIG. 8.



fo S = 1·0
S_m
S
T
$T_{MAX.}$
T_{start}
M
A
D

FIG. 9.

Here allowing 10 per cent. margin on the overload torque capacity gives—

$$\frac{T}{T_{max.}} = 0{\cdot}50 \times 0{\cdot}90 = 0{\cdot}45,$$

for which—

Equation (1) gives $S_m = 10{\cdot}5$ per cent., and

Equation (2) gives $\frac{T_{start.}}{T_{max.}} = 0{\cdot}208$,

or the starting torque would be only 20·8 per cent. of the maximum torque, *i.e.*—

$$\frac{T_s}{T} = \frac{0{\cdot}208}{0{\cdot}45} = 0{\cdot}46,$$

or a starting torque 46 per cent. of full-load torque.

As the relationships given by the above equations apply to any motor, they may be calculated and tabulated for general use; this has been done, and the values obtained are given in Table III., and also graphically in Fig. 10.

TABLE III.

Slip "S" per Cent. at Torque T.									
$\frac{T_{start.}}{T_{max.}}$ ...	0·20	0·30	0·40	0·50	0·60	0·70	0·80	0·90	1·0
$\frac{T}{T_{max.}}$ = 0·25	1·40	2·00	2·70	3·40	4·20	5·50	6·30	8·15	12·8
0·30	1·70	2·33	3·25	4·20	5·00	6·51	7·75	9·75	15·5
0·35	1·98	2·70	3·79	4·90	6·00	7·57	9·00	11·30	18·0
0·40	2·30	3·15	4·40	5·68	6·85	8·83	10·40	13·20	20·8
0·45	2·55	3·53	5·00	6·35	7·85	10·00	11·75	14·80	23·5
0·50	2·96	4·05	5·65	7·20	8·85	11·25	13·30	16·80	26·5
0·55	3·25	4·43	6·25	8·00	10·00	12·50	14·70	18·60	29·5

When using these curves in practice it is advisable to allow a margin of 10 or 15 per cent. on the guaranteed overload torque capacity on account of the presence of stator copper loss and ripples on the torque-slip curve discussed in Section II. of the paper.

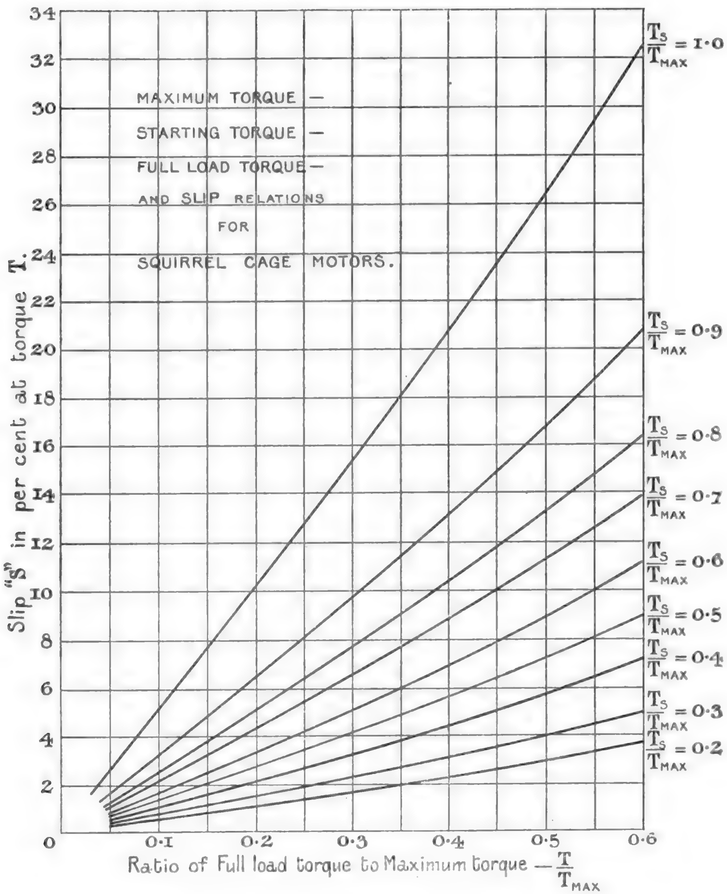

MAXIMUM TORQUE —
STARTING TORQUE —
FULL LOAD TORQUE —
AND SLIP RELATIONS
FOR
SQUIRREL CAGE MOTORS.
Slip "S" in per cent at torque T.
Ratio of Full load torque to Maximum torque — T/T_MAX
Ts/T_MAX = 1·0
Ts/T_MAX = 0·9
Ts/T_MAX = 0·8
Ts/T_MAX = 0·7
Ts/T_MAX = 0·6
Ts/T_MAX = 0·5
Ts/T_MAX = 0·4
Ts/T_MAX = 0·3
Ts/T_MAX = 0·2

FIG. 10.

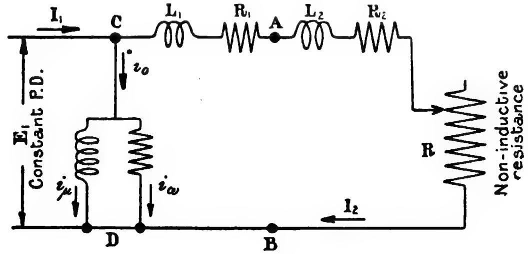

I1
C
L1
R1
A
L2
R2
i0
E1
Constant P.D.
iμ
ia
R
Non-inductive resistance
I2
D
B

FIG. 11.

The curves in Fig. 10 show clearly how rapidly a high starting torque—

1. Reduces the efficiency, and
2. Increases the difficulty of keeping the rotor cool.

APPENDIX.

When deducing the circle diagram from transformer principles it is convenient to assume at first that the rotor and stator windings are identical, that is, have a one-to-one transformation ratio. Considering one phase only, the windings of the motor are equivalent to the circuit shown in Fig. 11, the rotor being at standstill and the mechanical load represented by the I_2^2R watts loss in the external resistance R.

As the transformation ratio is unity, the primary and secondary windings are unnecessary in the diagram provided a branch circuit representing the no-load current is included between the points A and B.

It will be noticed that the exciting current i_0 which supplies the magnetising component i_μ and the hysteresis and eddy power component i_w, and which really flows between the points A and B, will decrease with increasing fall of pressure across L_1 and R_1 which takes place when I_1 is increased; however, no appreciable error is introduced by allowing i_0 to remain constant and moving this branch circuit from A B to C D, which gives the simple approximate equivalent circuit of the diagram.

The rotor current at standstill for any selected value of the fictitious load resistance R is given by—

$$I_2 = E_1 \div \sqrt{[(R_1 + R_2 + R)^2 + p^2 (L_1 + L_2)^2]}$$

which lags by an angle—

$$\mathrm{Sin}^{-1} \phi_2 = p (L_1 + L_2) \div \sqrt{[(R_1 + R_2 + R)^2 + p^2 (L_1 + L_2)^2]}$$

and therefore the rotor current may be written—

$$I_2 = \frac{E_1}{p (L_1 + L_2)} \times \sin \phi_2,$$

or the locus of the outer end of the rotor current vector in Fig. 1 is the arc of a circle having a diameter determined by the constants of the motor E_1, L_1, L_2, and the frequency.

In connection with this deduction it may be remarked that as the inductances L_1 and L_2 do not depend to any great extent upon

the air-gap, it is clear that the torque and power characteristics are nearly independent of the length of the air-gap.*

If the secondary coefficient of self-induction L_2 is increased with the object of limiting the starting current† a proportionate reduction in the diameter of the circle takes place, and this involves less power, torque, power factor, and efficiency over the whole running range of the motor.

* Cases occur in which the diameter of the circle is greater with a long air-gap.

† Fisher-Hinnen's method consists of inserting permanently in each circuit of a wound rotor a choking coil and resistance in parallel, with the object of providing a high-resistance circuit at starting and a low-resistance circuit when the rotor frequency falls.

The observed injury to the motors' performance by this system is due to the reduction of the diameter of the circle explained above.

JOURNAL

OF

The Institution of Electrical Engineers.

Founded 1871. *Incorporated* 1883.

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Proceedings of the Fortieth Annual General Meeting of the Institution of Electrical Engineers, held on Thursday, 16th May, 1912—Dr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting, held on 9th May, 1912, were taken as read, and confirmed.

Messrs. C. A. Baker, R. W. Hughman, M. J. E. Tilney, and G. H. C. Risch were appointed scrutineers to count the ballot papers for the election of an Associate Member of Council.

Messrs. W. C. P. Tapper and F. W. Main were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected:—

ELECTIONS.

As Member.

William Sutherland.

As Associate Members.

Claude Allen.
Frederick James Anderson.
Edgar Parkhouse Austin.
William Anselm Coates.
Herbert Musker Crellin.
John Wilfred Eastwood.
Ernest Robert Elliston.
William Lonsdale Gould.
John Joseph Gowen.
Peter Stewart Hay.

ELECTIONS (*continued*).

As Associate Members.

Frederic Augustus Kuhn.
Percy Lane.
David Ludwig Loewe.
Robert Martin Longman.
Edward Surtees Lowes.
Thomas Bernard Morgan.
Edward Reeves.
John Balfour Robertson.
Joseph Hamilton Robinson.
Frederick Barnett Soares.
James Arthur Sykes.
Frederick Jerrold Teago.
Edward William Thorp.
William Geoffry Ward.

As Associates.

Frederick Shah Dinenage.
Henry Fulton, M.R.C.S., L.R.C.P., M.D.
Hubert Alexander Gill.
Ernest Montague Hughman.
Geoffrey Freire Marreco.
Edward William T. Ward.
Arthur C. Wiley.

As Students.

Alphonse Levi Bedford.
Harold Douglas Bennett.
Eric Bilson.
William R. Bland.
Albert Thomas Chadwick.
Alfred Lawrence Lunn.
Andrew Hunter Munro.
Kuppanda Muttannah Muttannah.
Paul Edward Newman.
James Sutcliffe Partington.
John Herbert Squire.
John Chapman Wilson, B.Sc.
Lionel Sykes Wooler.

The business of the Annual General Meeting was then proceeded with.

REPORT OF THE COUNCIL

FOR THE YEAR 1911–12,

FOR PRESENTATION AT THE ANNUAL GENERAL MEETING OF 16TH MAY, 1912.

At this, the fortieth Annual General Meeting of the Institution of Electrical Engineers, the Council present to the members their Report for the year 1911–2.

MEMBERSHIP OF THE INSTITUTION.

The changes in the List of Members since the 1st May, 1911, are shown in the following table :—

	Hon. Mem.	Mem.	Assoc. Mem.	Assoc.	Stu.		TOTALS.
TOTALS AT 1ST MAY, 1911 ...	7	1,301	2,745	881	1,299		6,233
Additions during the year :—							
Elected	—	29	282	48	302	661	
Reinstated	—	2	9	5	8	24	
Transferred to	1	83	207	8	—	299	
TOTAL ADDITIONS FOR THE YEAR 1911–2	1	114	498	61	310	984	
Deductions during the year :—							
Deceased	1	13	9	12	3	38	
Resigned	—	10	33	37	52	132	
Lapsed	—	3	42	36	130	211	
Transferred from	—	1	70	51	177	299	
TOTAL DEDUCTIONS FOR THE YEAR 1911–2	1	27	154	136	362	680	
							304
TOTALS AT 1ST MAY, 1912 ...	7	1,388	3,089	806	1,247		6,537

The net increase of 304 shown above for the year compares with an average annual increase of 105 for the last five years.

Honours Conferred.

Honours have been conferred upon several members of the Institution during the past year :—

Sir J. J. Thomson, O.M., F.R.S., Honorary Member, has had conferred upon him the Order of Merit, and the Hon. Sir Charles Parsons, K.C.B., F.R.S., Honorary Member, and Sir Alfred Ewing, K.C.B., F.R.S., Member, have received the honour of appointment as Knights Commanders of the Bath. Sir William F. Barrett, F.R.S., Member, has received the dignity of Knighthood. Mr. I. C. Thomas, C.V.O., Member, and Mr. J. S. Pitkeathly, C.V.O., Associate Member, have been appointed Commanders of the Royal Victorian Order. Major-General R. M. Ruck, C.B., R.E., and Colonel H. C. L. Holden, R.A., C.B., F.R.S., Members, and Mr. A. M. J. Ogilvie, C.B., and Mr. A. W. Soward, C.B., Associates, have received the Order of Companion of the Bath.

The University of Manchester has conferred the Honorary Degree of Doctor of Science upon Mr. S. Z. de Ferranti, D.Sc., President, who has also been made an Honorary Member of the American Institute of Electrical Engineers.

Honorary Member.

The Council have pleasure in recording the announcement made at the Ordinary General Meeting of the 8th February last, that they had elected Mr. Charles Ernest Spagnoletti, Past President (1885), to be an Honorary Member of the Institution, in recognition of his long and distinguished connection with telegraphic science.

Local Honorary Secretaries Abroad.

The Council have appointed M. R. V. Picou to be Local Honorary Secretary and Treasurer for France, in the place of M. Xavier Gosselin, who now resides in England ; and Mr. Frank Pickering to the same office for the Cape, Natal, and Rhodesia, in the place of Mr. John Denham, who has removed to Johannesburg.

Members Deceased.

The Institution has to deplore the decease of one of its Honorary Members, Professor Antonio Pacinotti, of Pisa, who died on 24th March, 1912, aged 70 years. Every electrical engineer knows of his invention of the ring-wound armature, which, in 1861, he applied to a small magneto-electric machine of his own design, the use of which, both as motor and as generator, he published in 1864. He made other contributions to science in several directions, including suggestions for other improvements in dynamos, the permeability of magnetite, and the electric currents produced by metallic friction.

The complete list of those who have died during the past Session is as follows :—

Honorary Member.

Professor Antonio Pacinotti.

Members.

Ovide F. Domon.	Julius Mittelhausen.
John Crisp Fuller.	Edgar W. Mix.
Frederick T. J. Haynes.	John Edward Neale.
William Crammond Martin.	Edouard Rau.
William George Meddings.	William Dunlap Sargent.
Ernest Mercadier.	Percy Sewell Sheardown.

William Ryle Wright.

Associate Members.

John Brown, F.R.S.	Baron Augustus Mannerheim.
Edward Ayerst Davies.	William Henry M. Parr.
Laurence G. J. Epps.	George Gladman Sarney.
Henry Cooke Leake.	Harry George Young.

Isaac Probert.

Associates.

James Bernard Allen.	Jacques Florent Ducloy.
Thomas Newton Andrews.	William Heap.
James W. Boucher.	Harold Morton Middleton.
Peter Michael S. Brodie.	John Patrick Mulholland.
Edgar de Lautour.	James Oddie.

Students.

Harold Restarick Fisher.	Henry John K. Osborn.
Andrew Bell Mein.	Charles Frederick W. Sedgwick.
Robert Douglas Norman.	William Arthur Stephens.

Biographical notices of the deceased Members will be found in the *Journal.*

MEETINGS AND PAPERS.

During the past Session 18 General Meetings, 1 Special General Meeting, and 26 Council Meetings have been held. The usual Standing Committees have met regularly, and several Special Committees appointed by the Council for the consideration of special matters have also met, the total number of Committee Meetings held during the Session being 111.

There have been 47 meetings of Local Sections, viz., 7 at Birmingham, 7 at Dublin, 7 at Edinburgh and Glasgow, 12 at Manchester, 8 at Newcastle, and 6 at Leeds and Sheffield.

The Annual Dinner of the Institution took place at the Hotel Cecil, London, on 1st February, 1912. A report of the proceedings will be found in the *Journal*, vol. 48, p. 583.

Annual Dinners and other social functions were held at Birmingham, Bristol, Dublin, Glasgow, Leeds, Manchester, and Newcastle, which were well attended by members and guests.

The following is the list of papers for the Session, with the names of the authors and the places where read :—

Title.	Author.	Where Read.
Chairman's Address.	C. S. Vesey Brown, Member.	Newcastle.
Chairman's Address.	T. H. Churton, Member.	Leeds.
Chairman's Address.	W. Cramp, Member.	Manchester.
Chairman's Address.	F. A. Newington, Member.	Glasgow.
Chairman's Address.	S. L. R. Price, Associate Member.	Dublin.
"Some General Principles involved in the Electrical Driving of Rolling Mills."	C. A. Ablett.	London, Birmingham, Darlington, and Sheffield.
"Condensers in Series with Metal Filament Lamps."	A. W. Ashton, Associate Member.	London.
"Recent Developments in Steam Turbine Practice."	K. Baumann.	Manchester.
"The Mechanics of Electric Train Movement."	F. W. Carter, Associate Member.	Manchester.
The Third Kelvin Lecture.	Prof. H. du Bois.	London.
"Flashing-over in Commutator Machines; its Cause and Prevention."	W. W. Firth.	Newcastle.
"On the Power Factor and Conductivity of Dielectrics when tested with Alternating Electric Currents of Telephonic Frequency at various Temperatures."	Dr. J. A. Fleming, F.R.S., Member, and G. B. Dyke, Associate Member.	London.
"Weight Efficiency of Electric Motors and of Prime movers."	W. B. Hird, Member.	Edinburgh.
"Notes on Power Station Working."	J. W. Jackson.	Newcastle.
"Tariffs for Electrical Energy, with particular reference to Domestic Tariffs."	W. W. Lackie, Member.	London, Edinburgh, Manchester and Newcastle.
"High-Tension Porcelain Line Insulators."	J. Lustgarten, Associate Member.	Manchester.
"The Supply and Transmission of Power in Self-contained Road Vehicles and Locomotives."	J. C. Macfarlane, Member, and H. Burge, Associate Member.	London,

Title.	Author.	Where Read.
"The Behaviour of Direct-current Watt-hour Meters, more especially in relation to Traction Loads, with Notes on Erection and Testing."	S. W. Melsom, Associate Member, and W. H. Eastland.	London.
"Dynamos for Motor Road Vehicle Lighting."	J. D. Morgan, Associate.	Birmingham.
"An Automatic Starting Device for Asynchronous Motors."	N. Pensabene-Perez, Associate Member.	Birmingham.
"Notes on National and International Standards for Electrical Machinery."	Dr. R. Pohl, Member.	London and Leeds.
"Automatic Reversible Battery Boosters."	R. Rankin, Associate Member.	London, Birmingham, Glasgow, and Manchester.
"High-voltage Tests and Energy Losses in Insulating Materials."	E. H. Rayner, Member.	London.
"The Mechanical Design of Direct-Current Turbo-Generators."	R. J. Roberts, Associate Member.	Manchester.
"Electrical Meters on Variable Loads."	Prof. D. Robertson, Member.	London.
"The Corrugation of Rails."	A. Schwartz, Member, and R. G. Cunliffe, Associate Member.	Manchester.
"Residence Tariffs."	A. H. Seabrook, Member.	London.
"Specifications."	F. Sells, Associate.	Manchester.
"Yellow Flame Arcs."	M. Solomon, Member.	Birmingham.
"A Summary of the Theory of the Production of Electric Oscillations."	A. S. M. Sörensen, Associate Member.	Newcastle.
"The Diesel Engine from the User's Standpoint."	W. J. U. Sowter, Member.	Dublin.
"Small Electricity Supply Undertakings."	P. A. Spalding, Associate Member.	Dublin.
"Power Generation and Distribution in the Clyde Valley Electrical Power Company's Area."	D. A. Starr, Member.	Glasgow.
"Notes on an Avalanche which occurred on the Wellington (U.S.A.) Tunnel Electric Railway."	T. Stevens, Member, and J. B. Cox.	London.

Title.	Author.	Where Read.
"The Heat Paths in Electrical Machinery."	H. D. SYMONS, Associate Member, and M. WALKER, Member.	London and Manchester.
"Modern High-voltage Power Transformers in Practice; with special reference to a 'T' Three-unit System."	W. T. TAYLOR, Member.	London and Birmingham.
"The Development of the Circle Diagram for the Three-phase Induction Machine."	T. F. WALL, Associate Member.	Birmingham.

Three meetings were also allotted to a general discussion on "The Causes Preventing the more General Use of Electricity for Domestic Purposes."

In addition to the above-mentioned papers read at meetings the following have been accepted for printing in the *Journal*:—

Title.	Author.
"Report on Five Samples of Magnetic Sheet Material tested for Total Loss and Hysteresis at the Physikalisch-Technische Reichsanstalt, the Bureau of Standards, and the National Physical Laboratory."	A. CAMPBELL, Associate Member, H. C. H. BOOTH, and D. W. DYE.
"The Magnetic Properties of some Manganese Steels of Definite Composition."	EZER GRIFFITHS.
"Dynamometer Amperemeters and Voltmeters."	J. L. D. RIDSDALE, Student.
"An Indicating Coil for applying the Oscillograph to the Study of Commutation."	Professor D. ROBERTSON, Member.
"Hysteresis Loss in Iron taken through Unsymmetrical Cycles of Constant Amplitude."	M. ROSENBAUM, Associate Member.
"The Mutual Attractions or Repulsions of two Electrified Spherical Conductors."	Dr. A. RUSSELL, Member.
"The Losses in Induction Motors arising from Eccentricity of the Rotor."	C. F. SMITH, Member, and E. M. JOHNSON, Student.
"A Portable Electrical Instrument for the Detection of Combustible Gases and Vapours in Air."	L. J. STEELE, Member.
"1,000-volt Traction in the United States of America."	T. STEVENS, Member.

In future arrangements will be made for apparatus of interest to the members to be exhibited at the meetings.

Summer Meeting.

The first Summer Meeting of the Institution will be held in Glasgow from the 11th to the 15th June. The programme will consist

partly of the reading and discussion of papers and partly of the visiting of the industries and places of interest in the neighbourhood.

Scholarships.

The Council have awarded a Salomons Scholarship of the value of £50 to Richard Jeffrey Webb, of King's College, London; and a David Hughes Scholarship of the value of £50 to David Dunham, of the City and Guilds (Engineering) College, South Kensington.

Premiums.

The following premiums for papers have been awarded by the Council this year. In accordance with precedent, in deciding upon these awards the Council have not taken into account papers contributed by present members of Council.

The Institution Premium, value £25,

to Dr. J. A. Fleming, F.R.S., and Mr. G. B. Dyke, for their paper, "On the Power Factor and Conductivity of Dielectrics when tested with Alternating Electric Currents of Telephonic Frequency at various Temperatures."

The Ayrton Premium, value £10,

to Mr. J. Lustgarten, for his paper, "High-Tension Porcelain Line Insulators."

The Fahie Premium, value £10,

to Mr. W. Aitken, for his paper, "Automatic Telephone Exchanges."

The John Hopkinson Premium, value £10,

to Messrs. H. D. Symons and Miles Walker, for their paper, "The Heat Paths in Electrical Machinery."

The Kelvin Premium, value £10,

to Mr. E. H. Rayner, for his paper, "High Voltage Tests and Energy Losses in Insulating Materials."

The Paris Premium, value £10,

to Mr. R. J. Roberts, for his paper, "The Mechanical Design of Direct-Current Turbo-Generators."

An Extra Premium, value £10,

to Messrs. S. W. Melsom and H. C. Booth, for their paper, "The Heating of Cables with Current."

Students' Premiums.

A Students' Premium, value £10,

to Messrs. E. W. Moss and J. Mould, for their paper, "Homopolar Generators."

A Students' Premium, value £5,

to Mr. E. V. Pannell, for his paper, "On the Choice of Material for Overhead Line Conductors.

A Students' Premium, value £5,

to Mr. E. T. Caparn, for his paper, "The Electrical Working of Auxiliary Machinery on Modern Steamships."

A Students' Premium, value £5,

to Mr. R. G. Parrott, for his paper, "High-voltage Testing Transformers."

A Students' Premium, value £5,

to Messrs. P. R. Coursey and G. G. Dawson, for their paper, "An Account of some Experiments made with Various Wireless Telegraphy Transmitters ; and a Complete Description of an Inexpensive Apparatus for use on Short Distances."

Western Local Section.

On the receipt of a request from a number of members residing in the West of England and South Wales, the Council have established a Western Local Section for the holding of regular meetings for the reading of papers and for the discussion of electrical subjects. This Local Section will include provisionally members residing within 40 miles of Bristol or Cardiff, or in the Counties of Somerset, Wilts, Dorset, Devon and Cornwall, and the money grant for the expenses of the meetings will be based on the subscriptions of members residing within 40 miles of Bristol or Cardiff.

Students' Sections.

At the opening meeting of the Session an address to the Students was delivered by Mr. C. P. Sparks in the Lecture Theatre of the Institution.

Ten meetings of the Students' Section have been held, at which papers were read and discussed.

The Students' Committee organised a visit to Sweden in 1911, when works and places of interest were visited at Gothenburg, Trollhättan, Ludvika, Grangesberg, Vesterås, and Stockholm.

The Annual Dinner of the Students' Section was held at the Trocadero Restaurant, London, on 16th March, 1912.

The Glasgow and Manchester Students' Sections have each completed a successful session, having held six and eleven meetings respectively. Visits were made to various works by the kind permission of the firms concerned.

The Council have sanctioned the establishment of a Students' Section in Newcastle-on-Tyne, and have pleasure in recording that the formation of the Section is immediately connected with the addition of some 90 new Students from the Newcastle district to the membership of the Institution.

The Institution Building.

During the Session the Lecture Theatre and rooms of the Institution have been used by the Institution of Post Office Electrical Engineers, the Municipal Electrical Association, the British Electrical and Allied Manufacturers' Association, the National Electrical Contractors' Association, the Electric Supply Publicity Committee, the Committee for the Protection of Electrical Interests, the Associated Municipal Electrical Engineers of Greater London, the Electrical Trades Benevolent Fund, the Association of Consulting Engineers, the Telephone Society, the University of London Board of Studies for Electrical Engineering, the Faraday Society, the Röntgen Society, the Junior Institution of Engineers, the Society of Engineers, and the British Science Guild.

The Council have had much pleasure in placing at the disposal of H.M. Postmaster-General the Lecture Theatre and Institution rooms for the meetings of the International Radiotelegraphic Conference, which will be held in London from the beginning of June to the middle of July next.

The thanks of the Institution are due to Lady Kelvin for the marble bust of the late Lord Kelvin, Past-President, presented by her to the Institution. This bust has been executed by A. McF. Shannan, A.R.S.A.

Demonstration Apparatus.

The expenditure of a sum of £500 has been sanctioned by the Council for a motor-generator for the supply of continuous current at various voltages and alternating current at various frequencies and voltages for demonstration purposes, and also lecture tables, a new lantern, and sundry apparatus. This installation will enable authors to illustrate their papers and lectures experimentally. It is anticipated that the motor-generator will be completed and ready for use by next session.

The British Electrotechnical Committee.

The British Committee for 1911–12 is constituted as follows :—

Mr. A. Siemens (*President*).
Col. R. E. Crompton, C.B.
Mr. W. Duddell, F.R.S.
Mr. K. Edgcumbe.
Mr. S. Z. de Ferranti, D.Sc.
Sir John Gavey, C.B.
Dr. R. T. Glazebrook, C.B., F.R.S.
Mr. R. Kaye Gray.
Mr. R. Hammond.
Mr. R. W. Hammond.
Mr. C. Le Maistre.
Prof. T. Mather, F.R.S.
Mr. H. W. Miller.
Mr. W. M. Mordey.
Major W. A. J. O'Meara, C.M.G.
Mr. W. H. Patchell.
Sir W. H. Preece, K.C.B., F.R.S.
Lord Rayleigh, O.M., F.R.S.
Dr. A. Russell.
Mr. J. F. C. Snell.
Dr. S. P. Thompson, F.R.S.
Mr. A. P. Trotter.
Mr. E. B. Vignoles.
Mr. C. H. Wordingham.

Mr. P. F. Rowell (*Secretary*).

During the year progress has been made with the preparation of the definitions of Electrotechnical Terms, and the Committee have also had under consideration the subjects of Rating and Symbols, in connection with which meetings of International Delegates have recently been held in Paris.

International Electrotechnical Commission.

A meeting of the International Electrotechnical Commission was held at Turin from the 7th to the 13th September, 1911, at which the British Committee was represented by Mr. Alexander Siemens (*President of the Committee*); Mr. W. Duddell, F.R.S.; Mr. R. K. Gray, Professor T. Mather, F.R.S.; Major W. A. J. O'Meara, C.M.G.; Dr. S. P. Thompson, F.R.S.; and Mr. P. F. Rowell (*Secretary*).

The Council desire especially to draw the attention of members to the decisions of the Commission adopted at the Turin meeting:—

Symbols.

1. The following decisions are provisionally adopted by the Commission:—

(*a*) Instantaneous values of electrical quantities which vary with the time to be represented by small letters.

(*b*) Virtual or constant values of electrical quantities to be represented by capital letters.

(*c*) Maximum values of periodic electrical quantities to be represented by capital letters followed by the subscript "m."

(*d*) Magnetic quantities, constant or variable, to be represented by capital letters of either script, gothic, heavy-faced or any special type.

(*e*) Maximum values of periodic magnetic quantities to be represented by capital letters of either script, gothic, heavy-faced or any special type followed by the subscript "m."

(*f*) The following quantities to be represented by the following letters:—

Electromotive force	E	e		
Electric quantity	Q	q		
Self inductance	$\mathcal{L}$	$\mathfrak{L}$	$\mathbf{L}$	As examples only.
Magnetic force	$\mathcal{H}$	$\mathfrak{H}$	$\mathbf{H}$	
Magnetic flux density	$\mathcal{B}$	$\mathfrak{B}$	$\mathbf{B}$	

Length	L	l
Mass	M	m
Time	T	t

2. The letters I, E, R, are definitely adopted to represent the current, the electromotive force and the resistance respectively, in the algebraical expression for Ohm's law.

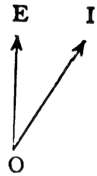
3. In all questions relative to alternating currents the expression "Reactive Power" is adopted to designate the quantity UI sin ϕ.

4. A special Committee on Symbols, consisting of one Delegate each from Belgium, France, Germany, Great Britain, Holland, Italy, Spain, Switzerland, and the United States of America, is appointed to continue the study of the subject, certain additional propositions of the French Committee and suggestions of the Dutch Committee being specially referred to.

Diagrams for Alternating Currents.

In the graphical representation of alternating electric and magnetic quantities, advance in phase shall be represented in the counter-clockwise direction.

Note.—In consequence, the impedance of a reactive coil of resistance R and inductance L is $R + \sqrt{-1}\, L\omega$ and that of a conductor of capacity C is $\frac{1}{\sqrt{-1}\, C\omega}$, where ω is equal to $2\pi \times$ frequency. It follows also that the diagram herewith represents the phase relations in a simple alternating-current circuit containing an impressed electromotive force OE and a lagging current OI.



Rating of Electrical Machinery and Apparatus.

1. As regards the power of continuous-current machinery :—

(*a*) The output of electrical generators is defined as the electrical power available at the terminals.

(*b*) The output of electrical motors is defined as the mechanical power available at the shaft.

(*c*) Both the electrical and mechanical powers to be expressed in international watts.

2. A Special Committee on the rating of electrical machinery and apparatus, consisting of one delegate each from Belgium, France, Germany, Great Britain, Italy, Sweden, Switzerland, and the United States of America, is appointed to continue the study of the subject.

Future Meetings.

1. The next official Meeting of the Commission is to be held in Berlin in 1913.

2. The Commission expresses its willingness to hold an official Meeting at San Francisco in 1915. The Central Office of the Commission is instructed, on the receipt of a request from the American Institute of Electrical Engineers, to co-operate in the organisation of an International Electrotechnical Congress at San Francisco at the same time.

"SCIENCE ABSTRACTS."

The work was continued in 1911 on the same lines as in 1910, the Physics Section being of about the same size, while the Electrical Engineering Section increased somewhat in bulk, comprising 1,281 abstracts and references, as against 1,104 in 1910. A slight modifica-

tion in the grouping of the matter is proposed for 1912, which, it is thought, will still further facilitate the finding of articles on any desired subject in the yearly index.

Wiring Rules.

The revised edition (the sixth) of the Wiring Rules, which was published in May, 1911, is in extensive use. The Rules have been adopted by forty-nine Fire Offices and the Bombay Fire Insurance Association and the Fire Salvage Association of Liverpool. They have also been accepted as standard practice and their use recommended by 232 Supply Authorities. More than 8,000 copies have been sold, and the Rules have also been reprinted in a large number of engineering handbooks and pocket-books.

Examination of Wiremen.

The Council have under consideration a scheme for the examination and certification of Wiremen by means of a uniform examination conducted from the headquarters of the Institution, and held at suitable centres in the United Kingdom.

Model General Conditions for Contracts.

The Council have continued the consideration of the Model General Conditions for Contracts, but the time required to obtain the views of interested bodies on the modifications proposed has been longer than had been anticipated, and has considerably delayed the publication of the revised edition.

Street Lighting Specification.

Early last year the Council inaugurated a committee consisting of representatives of this Institution, and of representatives nominated by the Councils of the Institution of Gas Engineers, the Institution of Municipal and County Engineers, and the Illuminating Engineering Society, to consider the preparation of a specification for street lighting to be issued jointly under the auspices of the various interested bodies. Several meetings have taken place, and good progress has been made with the work.

Industrial Committee.

The Council have decided to appoint a committee, the objects and constitution of which are as follows :—

1. An Industrial Committee to be appointed, to which shall be referred, for consideration and report, all industrial matters coming before the Council, and whose business shall also be to report to the Council on any industrial matters which, in the opinion of the Committee, affect the Electrical Industry, and in respect of which the Institution might usefully take action.

2. The Committee to consist of—

(a) 18 members drawn from the Members, Associate Members, and Associates of the Institution, at least 6 of whom shall be members of the Council;
(b) and, if so desired by the Council, other persons, not exceeding 6 in number, connected with other organisations, and not necessarily members of the Institution.

3. The Chairman of the Committee to be elected by the Council.

4. The existing Parliamentary Committee to be merged into the Industrial Committee, and the latter to take over the work of the Parliamentary Committee.

5. Subject to the Council's approval on each occasion, the Committee to arrange for special meetings of various branches of the Electrical Industry in the Institution building, at which the chair would be taken by a Chairman appointed by the Council.

6. The Council to inform other bodies of the appointment and existence of the Committee, and ask them to submit from time to time any matters which they consider should be taken up by the Institution.

Night Employment in Factories and Workshops.

It will be remembered that as the result of representations made by the Institution to the Home Office in 1902, electrical stations were granted special exemption from the provisions of the Factory and Workshops Act, 1901, as regards the night employment of boys.

In December last the Council received an inquiry as to whether the Institution would desire to tender evidence before the Home Office Departmental Committee on Night Employment in Factories and Workshops, a Committee appointed by the Home Secretary to report, *inter alia*, whether any or all of the exemptions granted under Sections 54, 55, and 56 of the Act should be repealed. The Council thereupon addressed inquiries to 100 electricity supply authorities and individuals, and it appeared from the replies received that there was no strong feeling on the subject, while a few pointed out that if the existing exemption were not maintained, there would be a slight increase in shift wages, and that the youths concerned would lose a useful training ground. The Council appointed as witnesses Mr. Frank Bailey and Mr. J. C. Wigham, who attended and gave evidence on these points before the Home Office Committee. The report of the Committee is not yet published.

Coal Mines Bill, 1911.

The Council carefully considered the provisions of the Coal Mines Bill, which was last year before Parliament, in its bearings upon the use of electricity in mines, and subsequently addressed a letter to the

Home Office urging the inconsistency of one of the provisions of the Bill, which prohibited the use of electricity in the presence of a certain percentage of inflammable gases, while permitting the use of naked lights under exactly similar conditions, and pointing out that no useful purpose could be served by such provisions. The Act, as passed by the Legislature, permits the use of electricity in the presence of a more reasonable percentage of gases, and also removes the inconsistency referred to above.

Benevolent Funds.

The Committee of Management report that the Benevolent Fund of the Institution shows a satisfactory increase for the past year. On 31st December, 1911, the capital account of the Fund stood at £4,000, as compared with £3,700 at the end of 1910. The donations to the Fund in 1911 include one of £203 17s. 7d. from the Executive of the Electrical Exhibition at Olympia, one of £45 19s. from the Building Trades' Gift to the Nation, one of £20 from the Committee of the Electrical Engineers' Ball, and one of £8 8s. from the "25" Club. The Fund also benefited to the extent of £200 under the will of the late Mr. G. Binswanger Byng, who had been an annual subscriber to the Fund since 1891. The Council desire to acknowledge their indebtedness to the generosity of these and other donors and subscribers who have supported the Fund.

The Wilde Benevolent Trust Fund stands at £1,846 4s. 6d.

Annual Accounts.

The Report of the Hon. Treasurer, Mr. Robert Hammond, is as follows :—

Excess of Revenue over Current Expenditure chargeable thereto.—The margin to the good on the Revenue Account is £1,274 2s. 1d. (page 678), which is carried to the credit of the General Fund. This amount compares with the previous year as follows:—

	£	s.	d.
In the 1911 Accounts	1,274	2	1
In the 1910 Accounts	3,053	0	2
Decrease of Excess in 1911 as compared with 1910	£1,778	18	1

Additions to Assets and Reduction of Liabilities.—In addition to the Current Expenditure, amounting to £13,763 1s. 11d. (page 678), against the year's Revenue of £15,037 4s. (page 677), the following amounts have been expended during the year :—

In adding to the Assets—

	£	s.	d.
Books and Binding for Library (page 687)	179	17	2
Furniture (page 681)	177	6	10

In Reducing the Liabilities—

	£	s.	d.
Obligatory Repayment of Mortgage under agreement with the Economic Life Assurance Society (page 684)... ...	625	13	3
	£982	17	3

Assets and Liabilities.—The Institution Building and Lease have been taken into the Accounts at cost, though, since the purchase, three years of the Lease have expired, in respect of which some deduction might have been made from the purchase price in order to arrive at the present value. This has not been done because the Institution have taken out Policies, payable at the expiry of the Lease in 1984, for the sum of £75,000, and it is considered that as long as the premiums on these Policies are regularly paid there is no need to erect a Depreciation Fund, they forming a satisfactory Depreciation Fund in respect of the value of the Building and Lease.

Taking therefore the Institution Building property and the Tothill Street property at cost, the Investments at cost, and the Library and Furniture, etc., at the values standing in the books after writing off depreciation—

	£	s.	d.
the Assets amount to (page 681)	101,739	1	0
against Liabilities (page 680)	39,335	0	3
leaving a margin to the good of	£62,404	0	9

which is made up as follows :—

	£	s.	d.
Life Compositions Fund	5,866	4	0
Building Fund	41,162	13	0
Kelvin Lecture Fund	912	10	10
General Fund	14,462	12	11

	£	s.	d.
This margin set against the margin to the good in 1910 of	59,835	1	8
shows an improvement for 1911 of...	£2,568	19	1

which is accounted for by—

	£	s.	d.
Entrance Fees (page 684)	929	1	0
Excess of Revenue over Current Expenditure (page 678)	1,274	2	1
Donations and Subscriptions to Building Fund (page 684)	116	5	6
Vellum Diplomas (page 684)	1	18	6
Life Compositions (page 686) ...	222	12	0
Kelvin Lecture Fund Dividend (page 686)	25	0	0
	£2,568	19	1

Trust Funds.—No alteration has taken place during the year under consideration in the two Scholarship Trust Funds, or in the Wilde Benevolent Trust Fund.

Life Compositions Fund.—This has been increased during the year by £222 12s. (page 11) and now stands at £5,866 4s. It includes all the Life Compositions that have ever been paid including an amount of £861 5s. in respect of deceased members. Under the Revised Articles this sum will be freed for transfer to the General Fund.

Library.

One hundred and one new books, in addition to the Eleventh Edition of the "Encyclopædia Britannica," have been purchased since May, 1911, and 246 books and pamphlets have been presented by members, authors, and publishers. The total number of readers during the past twelve months was 1,294, of whom 85 were non-members. The thanks of the Institution are due to Mr. R. K. Gray, who for many months has paid the wages of a skilled book-repairer engaged in repairing the old bindings in the Ronalds and the Institution Libraries.

The trustees of the Ronalds Library held a meeting in February last, and after inspecting the books, stated that in their opinion the terms of the Trust Deed had been carried out by the Institution in a most satisfactory manner.

Museum.

Several additions have been made to the collection of historical apparatus, among the more notable being two Gramme dynamos used for the lighting of the Thames Embankment in 1878–9 (presented by Mr. H. Hirst and the Electrical Standardising, Testing, and Training Institution, respectively), a collection of telephone apparatus (presented by the National Telephone Company), one of the original models of the Thomson Siphon Recorder (presented by

the Eastern Telegraph Company), and a set of porcelain insulators (presented by Mr. J. C. Chambers).

There has also been presented to the Institution by Mr. R. K. Gray, the gold medal given to the late Sir Samuel Canning by the American Chamber of Commerce, at Liverpool, on the completion of the 1865–66 Atlantic Cables between Valentia Island and Heart's Content, Newfoundland.

APPENDIX TO REPORT.

TRANSACTIONS, PROCEEDINGS, ETC., RECEIVED BY THE INSTITUTION.

BRITISH.

British Association for the Advancement of Science, Reports.
Cambridge Philosophical Society, Proceedings.
Chartered Institute of Patent Agents, Transactions.
Faraday Society, Transactions.
Greenwich Magnetical and Meteorological Observations.
Incorporated Institution of Automobile Engineers, Proceedings.
Incorporated Municipal Electrical Association, Proceedings.
Institute of Chemistry, Proceedings.
Institute of Marine Engineers, Transactions.
Institute of Metals, Journal.
Institution of Civil Engineers, Proceedings.
Institution of Engineers and Shipbuilders in Scotland, Transactions.
Institution of Mechanical Engineers, Proceedings.
Institution of Mining and Metallurgy, Transactions and Bulletin.
Institution of Naval Architects, Transactions.
Institution of Post Office Electrical Engineers, Papers.
Iron and Steel Institute, Journal and Carnegie Memoirs.
Liverpool Corporation Tramways, Annual Reports.
Liverpool Engineering Society, Proceedings.
Manchester Literary and Philosophical Society, Memoirs and Proceedings.
Municipal School of Technology, Manchester, Journal.
National Physical Laboratory Reports, and Collected Researches.
North-East Coast Institution of Engineers and Shipbuilders, Transactions.
North of England Institute of Mining and Mechanical Engineers, Transactions.
Physical Society, Proceedings.
Röntgen Society, Journal.
Royal Dublin Society, Scientific and Economic Proceedings.
Royal Institution, Proceedings.
Royal Meteorological Society, Quarterly Journal and Monthly Notes.
Royal Society, Philosophical Transactions and Proceedings.

Royal Society of Arts, Journal.
Royal Society of Edinburgh, Transactions and Proceedings.
Royal United Service Institution, Journal.
Rugby Engineering Society, Proceedings.
Society of Chemical Industry, Journal.
Society of Engineers, Transactions.
South Wales Institute of Engineers, Proceedings.
Surveyors' Institution, Transactions and Professional Notes.
Tramways and Light Railways' Association, Journal.

COLONIAL.

Canadian Electrical Association, Proceedings.
Canadian Society of Civil Engineers, Transactions.
Engineering Association of New South Wales, Proceedings.
Engineering Society of Toronto, Transactions.
Indian Telegraph Department, Administration Reports.
Royal Society of Queensland, Proceedings.
Royal Society of Victoria, Proceedings.
South African Institution of Electrical Engineers, Transactions.
South Australia, Meteorological Observation Reports.
Sydney University of Engineering, Proceedings.
Western Australian Institution of Engineers, Proceedings.

AMERICAN.

American Academy of Arts and Sciences, Proceedings.
American Electrochemical Society, Transactions.
American Institute of Electrical Engineers, Transactions and Proceedings.
American Institute of Mining Engineers, Transactions and Bulletin.
American Philosophical Society, Proceedings.
American Society of Civil Engineers, Proceedings.
American Society of Mechanical Engineers, Transactions and Journal.
Bureau of Standards, Washington, Bulletin.
Engineers' Club of Philadelphia, Proceedings.
Franklin Institute, Journal.
Illuminating Engineering Society, N. Y., Transactions.
National Electric Light Association, Transactions.
Smithsonian Institution, Reports.
U.S. Official Patent Gazette.
U.S. Ordnance Report.
Western Society of Engineers, Journal.

AUSTRIAN.

Kaiserliche Akademie der Wissenschaften, Wien, Sitzungsberichte.

BELGIAN.

Association des Ingénieurs Électriciens sortis de l'Institut Électrotechnique Montefiore, Bulletin.

DUTCH.

Koninklijk Institut van Ingenieurs, Tijdschrift.
Koninklijke Akademie van Wetenschappen, Amsterdam, Proceedings.

FRENCH.

Académie des Sciences, Comptes Rendus Hebdomadaires des Séances.
Bureau des Longitudes, Annuaire.
Société des Anciens Élèves des Ecoles Nationales d'Arts et Métiers Bulletin Technologique.
Société des Ingénieurs Civils, Mémoires.
Société Française de Physique, Bulletin des Séances.
Société Internationale des Électriciens, Bulletin.
Société Scientifique Industrielle de Marseille, Bulletin.

GERMAN.

Physikalische Technische Reichsanstalt, Abhandlungen.
Schiffbautechnische Gesellschaft, Jahrbuch.
Verein Deutscher Ingenieure, Zeitschrift.
Verein zur Beförderung des Gewerbfleisses, Verhandlungen.

ITALIAN.

Associazione Elettrotecnica Italiana, Atti.
Reale Accademia dei Lincei, Atti e Memorie

JAPANESE.

College of Science, Kyoto Memoirs.

SWEDISH.

K. Svenska Vetenskaps-Akademien, Arkiv för Matematik, etc.

SWISS.

Association Suisse des Electriciens, Annuaire, et Bulletin.

LIST OF PERIODICALS RECEIVED BY THE INSTITUTION.

BRITISH.

Aero.
Automobile Owner.
Cassier's Magazine.
Central.
Colliery Guardian.
Electrical Engineering.
Electrical Industries.
Electrical Review.
Electrical Times.
Electrician.
Electricity.
Electrics.
Engineer.
Engineering.
Engineering Magazine.
Engineering Review.
English Mechanic.
Illuminating Engineer.
Illustrated Official Journal, Patents.
Iron and Coal Trades Review.
Light Railway and Tramway Journal.
Marconigraph.
Mechanical Engineer.
Mining Journal.
Nature.
Page's Weekly.
Philosophical Magazine.
Post Office Electrical Engineers' Journal.
Railway News.
Railway Times.
Royal Engineers' Journal.
Tramway and Railway World.
Vulcan.

COLONIAL.

Australian Mining Standard.
Australian Official Journal of Patents.
Canadian Machinery.
Electrical News (Toronto).
Indian Industries and Power.
Mining and Engineering Review.
Power House.

AMERICAN.

American Journal of Science.
Electric Journal.
Electric Railway Journal.
Electrical Review.
Electrical World.
Engineering News.
India Rubber World.
Journal of the Telegraph.
Metallurgical and Chemical Engineering.
Physical Review.
Scientific American.
Telegraph Age.
Telephony.
Terrestrial Magnetism and Atmospherical Electricity.

AUSTRIAN.

Elektrotechnik und Maschinenbau.

BELGIAN.

Revue de l'Electricité.

DANISH.

Teknisk Tidsskrift.

DUTCH.

De Ingenieur.

FRENCH.

Annales des Postes, Télégraphes, et des Téléphones.
Archives des Sciences Physiques et Naturelles.
Electricien.
Houille Blanche.
Industrie Électrique.
Journal de Physique.
Journal Télegraphique.
Lumière Électrique.
Mois Scientifique et Industriel.
Portefeuille Economique des Machines.
Revue de l'Ingénieur.
Revue Électrique.

GERMAN.

Annalen der Physik.
Annalen der Physik, Beiblätter.
Elektrische Kraftbetriebe und Bahnen.
Elektrotechnische Zeitschrift.
Elektrotechnischer Anzeiger.
Fortschritte der Elektrotechnik.
Glückauf.
Jahrbuch der drahtlosen Telegraphie.
Jahrbuch der Elektrochemie.
Jahrbuch der Radioaktivität.
Physikalische Zeitschrift.
Zeitschrift für Elektrochemie.
Zeitschrift für Elektrotechnik und Maschinenbau.
Zeitschrift für Instrumentenkunde.
Zeitschrift für Schwachstromtechnik.

ITALIAN.

L'Elettricista.
L'Elettricita.
Giornale del Genio Civile.
Il Nuovo Cimento.
Rivista Tecnica delle Ferrovie Italiane.

SPANISH.

La Ingenieria.

SWEDISH.

Svensk Export.

SWISS.

Schweizerische Elcktrotechnische Zeitschrift.

The Institution of

STATEMENT OF EXPENDITURE AND
ENDED 31st

Dr. EXPENDITURE.

	£	s.	d.	£	s.	d.
To MANAGEMENT :—						
Salaries and Wages	2,400	8	11			
Accountants' Fees	21	0	0			
Printing	427	11	5			
Stationery and Office Requisites	191	2	11			
Addressing (Notices)	53	9	2			
Postage (Correspondence and Notices) ...	385	17	7			
Telephone	48	2	6			
Travelling Expenses	61	8	9			
Bank Charges	6	9	3			
				3,595	10	6
„ INSTITUTION BUILDING :—						
Ground Rent	2,201	0	0			
Rates and Taxes	1,982	15	2			
Lighting	60	3	6			
Firing	36	19	4			
Insurance	57	3	2			
Repairs	259	11	9			
Letting Expenses	57	15	0			
Household Requisites and Cleaning... ...	57	6	10			
				4,712	14	9
„ INTEREST ON MORTGAGES :—						
Institution Building	1,059	12	8			
Tothill Street Property	488	15	0			
				1,548	7	8
„ SINKING FUND PREMIUMS				277	12	2
„ FURNITURE REPAIRS AND RENEWALS				16	9	4
„ JOURNAL :—						
Printing	1,414	12	5			
Postage	551	13	7			
Addressing	16	18	7			
Wrappers	17	11	5			
Advertising	34	10	0			
	2,035	6	0			
Less Receipts—						
Sales £283 17 11						
Advertisements 312 0 0						
	595	17	11			
				1,439	8	1
Carried Forward				£11,590	2	6

Electrical Engineers.

INCOME FOR THE YEAR DECEMBER, 1911.

INCOME. Cr.

		£	s.	d.
By Subscriptions		11,779	14	6
,, Dividends on Investments		77	3	0
,, Interest		39	19	8
,, Wiring Rules		61	18	0
,, Model General Conditions		7	5	11
,, Institution Building :—				
Rent from Tenants		2,975	0	0
,, Tothill Street Property :—				
Rent from Tenants	£447 17 8			
Less Ground Rent, Rates, Taxes, &c. ...	351 14 9			
		96	2	11
Carried Forward		£15,037	4	0

STATEMENT OF EXPENDITURE AND ENDED 31st

Dr. EXPENDITURE—*continued.*

	£	s.	d.	£	s.	d.
Brought Forward				11,590	2	6
To "SCIENCE ABSTRACTS"—						
Salaries, Abstracting, Printing, Postage, etc.	1,629	8	6			
Less Subscriptions, Sales, and Advertisements	1,362	16	3			
				266	12	3
" MEETINGS :—						
Advance Proofs, Refreshments, etc.	197	16	4			
Reporting	74	11	0			
				272	7	4
" LOCAL SECTIONS :—						
Money Grants	616	4	4			
Travelling Expenses	142	18	3			
				759	2	7
" PREMIUMS				110	17	11
" BRITISH ELECTROTECHNICAL COMMITTEE				96	13	11
" CONVERSAZIONE				238	2	2
" ANNUAL DINNER				48	7	8
" DEPRECIATION :—						
Library	167	7	8			
Furniture	97	13	2			
				265	0	10
" LEGAL EXPENSES				37	17	2
" MISCELLANEOUS EXPENSES				77	17	7
				*13,763	1	11
" BALANCE carried to General Fund				1,274	2	1
				£15,037	4	0

* This amount does not include the following Expenditure incurred in reducing the Liabilities, or adding to the Assets :—

	£	s.	d.
Obligatory Repayment of Mortgage under agreement with the Economic Life Assurance Society (see Building Fund, page 684)	625	13	3
Books and Binding for Library (see page 687) ...	179	17	2
Furniture and Fittings (see page 681)	177	6	10
	£982	17	3

INCOME FOR THE YEAR DECEMBER, 1911—(*continued*).

INCOME—*continued*. Cr.

	£	s.	d.
Brought Forward	15,037	4	0
	£15,037	4	0

BALANCE SHEET,

Dr.

LIABILITIES.

	£ s. d.	£ s. d.
To Salomons Scholarship Trust Fund		33 16 4
„ David Hughes Scholarship Trust Fund :—		
Capital uninvested	1 5 0	
Income	9 1 6	
		10 6 6
„ Wilde Benevolent Trust Fund		181 12 1
„ Life Compositions Fund		5,866 4 0
„ Building Fund		41,162 13 0
„ Kelvin Lecture Fund :—		
Capital	862 10 10	
Income	50 0 0	
		912 10 10
„ Sundry Creditors		2,675 9 3
„ Economic Life Assurance Society		36,274 8 10
„ Local Sections :—		
Due to Hon. Sec. Newcastle Local Section	19 7 9	
„ „ „ Scottish Local Section	9 3 6	
		28 11 3
„ Subscriptions received in advance		91 6 0
„ Foreign Visit Fund		39 10 0
„ General Fund		14,462 12 11

ROBERT HAMMOND,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

£101,739 1 0

We beg to report that we have audited the Balance Sheet of the Institu-
together with the annexed Statements of Account. We have obtained all the
ments are correct, and the Balance Sheet is properly drawn up so as to
according to the best of our information and the explanations given to

ALLEN, BIGGS & CO.,
Chartered Accountants,
147, Leadenhall Street, E.C.

11th April, 1912.

31st DECEMBER, 1911.

Cr.

ASSETS.

	£	s.	d.	£	s.	d.
By General Fund Investment (at cost)				1,659	5	8
„ Life Compositions Fund Investment „				611	6	4
„ Kelvin Lecture Fund Investment „				862	10	10
„ Tothill Street Buildings and Site „				19,260	17	1
„ Institution Building and Lease * ... „				73,028	6	10
„ Sundry Debtors				968	4	7
„ Local Sections:—						
Due from Hon. Sec. Birmingham Local Section	8	4	8			
„ „ Hon. Sec. Manchester Local Section	13	5	7			
„ „ Hon. Sec. Yorkshire Local Section	3	5	9			
				24	16	0
„ Library				1,506	9	0
„ Furniture and Fittings:—						
As per last Balance Sheet	1,776	1	2			
Additions during 1911	177	6	10			
	1,953	8	0			
Less Depreciation	97	13	2			
				1,855	14	10
„ Fire Insurance Premiums Paid in Advance	238	9	3			
„ Rates Paid in Advance	34	14	5			
				273	3	8
„ Cash:—At Institution Bankers'	1,479	3	2			
Petty Cash	27	10	11			
P.O. Savings Bank (Wilde Benevolent Trust Fund)	181	12	1			
				1,688	6	2
				£101,739	1	0

* Policies payable on the 24th of June, 1984, have been taken out with the Alliance Assurance Co. for £25,000, and with the Economic Life Assurance Co. for £50,000, as provision for amortisation of expenditure on the Institution Building and Lease. The total amount of premiums paid to date is £738 11s. 10d., the surrender value of which at date is £364 15s. 11d.

tion of Electrical Engineers, dated 31st December, 1911, and above set forth, information and explanations we have required. In our opinion the State-exhibit a true and correct view of the state of the Institution's affairs us and as shown by the books of the Institution.

H. ALABASTER,
SIDNEY SHARP, } *Honorary Auditors.*

Dr.

	£ s. d.	£ s. d.
To Excesses of Income over Expenditure to 31st December, 1910		39,688 13 0
Add Excess of Income over Expenditure for 1911		1,274 2 1
		40,962 15 1
Less Transfers (as per last Account) :—		
To Building Fund	25,637 11 4	
To Kelvin Lecture Fund	862 10 10	
		26,500 2 2
		£14,462 12 11

FUND.

Cr.

	£	s.	d.	£	s.	d.	£	s.	d.
By Investment (at cost) :—									
£1,900 Natal Zululand Railways 3% Debentures							1,659	5	8
„ Balance made up as follows :—									
ASSETS.									
Sundry Debtors	993	0	7						
Cash in Hand	1,688	6	2						
Furniture	1,855	14	10						
Library	1,506	9	0						
Rates and Insurance Premiums Paid in Advance	273	3	8						
Loan to Building Fund ...	9,630	1	10						
				15,946	16	1			
LIABILITIES.									
Uninvested Balances of Special Funds	348	2	4						
Sundry Creditors	2,704	0	6						
Subscriptions in Advance ...	91	6	0						
				3,143	8	10			
							12,803	7	3
							£14,462	12	11

BUILDING

Dr.

	£	s.	d.	£	s.	d.
To Amount (as per last Account) :—						
Transfers from General Fund (1894 to 1908)	25,637	11	4			
„ „ Entrance Fees Fund (1908 to 1910)	6,737	7	6			
Revenue from Tothill Street Property (1904 to 1909)	3,323	4	7			
Interest and Dividends (1896 to 1909) ...	2,363	5	2			
Donations and Subscriptions to Building Fund (1899 to 1910)	1,917	10	6			
Surplus from Vellum Diplomas (1899 to 1910)...	136	8	11			
				40,115	8	0
„ Additions during 1911 :—						
Transfer from Entrance Fees Fund ...	929	1	0			
Donations and Subscriptions to Building Fund	116	5	6			
Surplus from Vellum Diplomas	1	18	6			
				1,047	5	0
				41,162	13	0
„ Balance made up as follows :—						
Due to Life Compositions Fund	5,222	0	3			
Due to General Fund	9,630	1	10			
Due to the Economic Life Assurance Society :—						
On mortgage of :—						
Institution Building ... 26,000 0 0						
Less Repaid—						
Previous to 1911 ... 599 17 11						
During 1911 625 13 3						
1,225 11 2						
	24,774	8	10			
Tothill Street Buildings and Site ...	11,500	0	0			
				51,126	10	11
				£92,289	3	11

ENTRANCE FEES

Dr.

	£	s.	d.
To Entrance Fees from 1902 to 1910—			
(As per last Account)	6,737	7	6
, Entrance Fees received in 1911	929	1	0
	£7,666	8	6

FUND.

Cr.

	£	s.	d.
By Tothill Street Buildings and Site (as per last Account) ...	19,260	17	1
„ Institution Building and Lease (as per last Account) ...	73,028	6	10
	£92,289	3	11

FUND.

Cr.

	£	s.	d.
By Amounts transferred to Building Fund :—			
Transferred previous to 1911 (as per last Account)	6,737	7	6
Transferred in 1911	929	1	0
	£7,666	8	6

LIFE COMPOSITIONS

Dr.

	£	s.	d.
To Amount (as per last Account)	5,643	12	0
„ Life Compositions received in 1911	222	12	0
	£5,866	4	0

KELVIN LECTURE

Dr.

	£	s.	d.
To Amount (as per last Account)	887	10	10
„ Dividends	25	0	0
	£912	10	10

LIBRARY.

Dr.

	£	s.	d.
To Amount (as per Balance Sheet)	1,506	9	0
	£1,506	9	0

FUND.

Cr.

	£	s.	d.
By Investment (at cost) :—			
£700 Natal Zululand Railways 3% Debentures	611	6	4
„ Loan to Building Fund	5,222	0	3
„ Balance Uninvested	32	17	5
	£5,866	4	0

FUND.

Cr.

	£	s.	d.
By Investment (at cost) :—			
£1,000 2½% Consolidated Stock	862	10	10
„ Balance Uninvested	50	0	0
	£912	10	10

LIBRARY.

Cr.

	£	s.	d.
By Outlays on Books, Pictures, etc., to 31st December, 1910 ...	2,648	4	11
Less Provision for Depreciation (1901–10)	1,154	5	5
As per last Balance Sheet	1,493	19	6
„ Expenditure on Books and Binding in 1911	179	17	2
	1,673	16	8
Less 10% Depreciation for 1911	167	7	8
	£1,506	9	0

SALOMONS SCHOLARSHIP

Dr.

	£	s.	d.
To Amount (as per last Account)	2,126	19	3
	£2,126	19	3

SALOMONS SCHOLARSHIP

Dr.

	£	s.	d.
To Amount paid to Scholars in 1911...	75	0	0
„ Balance carried to Balance Sheet	33	16	4
	£108	16	4

DAVID HUGHES SCHOLARSHIP

Dr.

	£	s.	d.
To Amount (as per last Account)	2,000	0	0
	£2,000	0	0

DAVID HUGHES SCHOLARSHIP

Dr.

	£	s.	d.
To Amount paid to Scholars in 1911...	75	0	0
„ Balance carried to Balance Sheet	9	1	6
	£84	1	6

WILDE BENEVOLENT

Dr.

	£	s.	d.
To Amount (as per last Account)	1,846	4	6
	£1,846	4	6

WILDE BENEVOLENT

Dr.

	£	s.	d.
To Balance carried to Balance Sheet	181	12	1
	£181	12	1

TRUST FUND.

		Cr.	
	£	s.	d.
By Investments (at cost) :—			
£1,500 New South Wales 3½ % Stock	1,556	5	9
£500 Cape of Good Hope 3½ % Stock	570	13	6
	£2,126	19	3

TRUST FUND (Income).

		Cr.	
	£	s.	d.
By Balance (as per last Account)	38	16	4
„ Dividends received in 1911	70	0	0
	£108	16	4

TRUST FUND.

		Cr.	
	£	s.	d.
By Investment (at cost) :—£2,045 Staines Reservoirs 3 % Guaranteed Debenture Stock	1,998	15	0
„ Balance carried to Balance Sheet	1	5	0
	£2,000	0	0

TRUST FUND (Income).

		Cr.	
	£	s.	d.
By Balance (as per last Account)	22	14	6
„ Dividends received in 1911	61	7	0
	£84	1	6

TRUST FUND.

		Cr.	
	£	s.	d.
By Investments (at cost):—			
£875 Great Eastern Railway Metropolitan 5 % Guaranteed Stock	1,493	16	3
£215 North Eastern Railway 4 % Guaranteed Stock ...	250	19	9
£100 London County 3½ % Stock	101	8	6
	£1,846	4	6

TRUST FUND (Income).

		Cr.	
	£	s.	d.
By Balance (as per last Account)	122	9	5
„ Dividends received in 1911	55	17	0
„ Interest do. do.	3	5	8
	£181	12	1

The Institution of

Statement of Accounts

Dr. CAPITAL

	£	s.	d.
To Balance as per last Account	3,700	0	0
„ Transfer from Income	300	0	0
	£4,000	0	0

Dr. INCOME AND

	£	s.	d.
To Balance as per last Account	215	6	3
„ Dividends on Investments...	119	6	6
„ Interest on Deposit	7	1	0
„ Donations under £5	8	11	6
„ Donations of £5 and over	483	14	1
„ Annual Subscriptions	82	0	6
	£915	19	10

Dr. BALANCE

	£	s.	d.
To Capital	4,000	0	0
„ Income and Expenditure Account	605	7	5
	£4,605	7	5

We have examined the above Accounts with the Receipt Book, Cash Book, and we find them to be correct.

8*th May*, 1912.

LENT FUND OF

Electrical Engineers.

to December 31, 1911.

ACCOUNT. Cr.

	£	s.	d.
By Balance carried to Balance Sheet, viz. :—			
Investments—			
£961 7s. 7d. Cape of Good Hope 3 % Stock	950	0	0
£593 1s. 7d. New South Wales 3% Stock	600	0	0
£420 Great Eastern Railway 4 % Pref. Stock...	503	18	3
£600 North Staffordshire Railway 3 % Deb. Stock	551	0	9
£750 East Indian Railway 3½ % Deb. Stock	737	18	0
£300 London and North Western Railway 4 % Guar. Stock	333	11	6
£330 New Zealand 3½ % Stock...	321	2	10
Cash	2	8	8
	£4,000	0	0

EXPENDITURE ACCOUNT. Cr.

				£	s.	d.
By Grants				8	0	0
„ Postages, Printing, &c.				2	12	5
„ Transfer to Capital...				300	0	0
„ Balance carried to Balance Sheet, viz. :—						
£170 New Zealand 3½ % Stock	£165	15	8			
Due from Sundry Debtors	1	0	0			
Cash	438	11	9			
				605	7	5
				£915	19	10

SHEET. Cr.

				£	s.	d.
By Investments (Capital Account)—						
£961 7s. 7d. Cape of Good Hope 3 % Stock				950	0	0
£593 1s. 7d. New South Wales 3 % Stock				600	0	0
£420 Great Eastern Railway 4 % Pref. Stock				503	18	3
£600 North Staffordshire Railway 3 % Deb. Stock				551	0	9
£750 East Indian Railway 3½ % Deb Stock				737	18	0
£300 London and North Western Railway 4 % Guar. Stock				333	11	6
£330 New Zealand 3½ % Stock				321	2	10
				3,997	11	4
„ Investment (Income Account)—						
£170 New Zealand 3½ % Stock				165	15	8
„ Sundry Debtors				1	0	0
„ Cash—						
At Bankers'	£435	7	7			
Petty Cash	5	12	10			
				441	0	5
				£4,605	7	5

Bankers' Pass Book, and Vouchers, also Bankers' Certificate of Investments,

H. ALABASTER, }
SIDNEY SHARP, } *Honorary Auditors.*

The PRESIDENT: The Annual Report has been circulated; it has been sent to all the members, and there is no occasion for me to take up your time in going over it afresh. I hope those members who are here have read it, and I hope it will be read generally by the membership of the Institution. I would like, however, to make one remark with regard to the extension of the Institution and its usefulness. We are at present actively engaged through our friends in South Africa in the formation of a new Local Section in Johannesburg. I may say that the arrangements are going on satisfactorily, and we hope soon to have a large and active section in Johannesburg to look after the interests of the Institution and to keep in touch with the home body. We are desirous of doing the same sort of thing in Canada. You all know how Canada is progressing, and the immense amount of electrical business that is being done there. In Canada, of course, the case is somewhat different; we are in competition with our friends and neighbours on the other side of the frontier, who are very active and have a large membership in Canada. Still, we think without interfering with them in any way, we should have a large membership of our Institution over in Canada, and we are taking all the necessary steps to get a Canadian Section started. I have to move "That the Annual Report as circulated be received and adopted."

Mr. A. A. CAMPBELL SWINTON: I have much pleasure in seconding the motion.

The resolution having been put, was declared to be carried unanimously.

Mr. R. HAMMOND: Mr. President and Gentlemen, the resolution which has been committed to me is: "That the Statement of Accounts and Balance Sheet for 1911, as presented, be received and adopted." Copies of the Accounts have been circulated with the Annual Report, and we think they are so clear that possibly there is no need for me to give any explanation of them. But at the same time it has been for many years the custom of this Institution to allow the Honorary Treasurer a few minutes at the Annual Meeting to draw attention to two or three points in the Accounts, and I venture to avail myself of that custom to-night. The first point to which I would like to draw your attention is the very satisfactory revenue which we received last year from the members in the form of subscriptions. I put that first because that is naturally the backbone of our financial prosperity. As long as our subscriptions keep up to the standard, or are an increase upon the standard of former years, we feel that we are in a healthy position. Last year the amount received in the form of subscriptions was £11,779. Those of us who have been elected by your votes in the past ten years, and have in this way been authorised to speak on your behalf on these occasions, are able to remind you that in 1901 our revenue from subscriptions amounted to £5,574, and ten years later we are able to announce a subscription list of £11,779. Turning to the other side of the Account, we are glad to be able to state that, after paying the whole of the costs of management, the upkeep and ground rent of this building, the interest upon all

the mortgages, and the expenditure upon the Sinking Fund from time to time, by means of which the purchase price of this building will be repaid in full at the end of seventy-five years; after bearing the whole cost of the *Journal*, *Science Abstracts*, and the Local Sections, etc., etc., there still remains an amount to the good, on what might be termed in the case of a company our Trading Account, *i.e.*, our Revenue and Expenditure Account, of £1,274. Those who at a recent meeting spoke of the Institution as being in a bad way financially, had not, I think, foreseen these accounts. The net result is that we are £1,274 to the good on the past year's Revenue Account. To that £1,274 we are able to add the amount received in the form of entrance fees. Following again an old custom of the Institution, we do not treat entrance fees as a revenue amount; we only treat subscriptions under that head. The entrance fees for last year amounted to £929 1s., a larger sum than has ever before been reached in the history of the Institution, meaning, of course, that we had more members entering last year than we ever had before. There are sundry other items with which I need not trouble you, but which are set out in the Accounts, bringing up the amount to the good in the year to the important sum of £2,568. I am laying before you a Budget, and you may be interested to have extracted from the Accounts what we did with the £2,568. Looking forward a bit, and reading what is prognosticated in the report, we shall be able to report next year that we have added some very important apparatus, by means of which the experiments at our lectures and papers will be made much more effective. But that is a question for the future Honorary Treasurer; I am concerned with the past, and I am able to say that we used the £2,568 first in making a reduction of our mortgage, it being a duty which we have taken upon ourselves to decrease by an annual sum the amount of money borrowed by the Institution. That got rid of £625 13s. 3d. We added to the books in our Library to the extent of £179 17s. 2d., and we added certain articles of furniture and improvements to the common room amounting to £177; so that our total expenditure on the debit side of our budget amounted to £982 out of the £2,568, leaving us a sum of over £1,500 in cash to the good, which we have not specially earmarked, but have kept in hand for any emergencies that may arise. The result of this improvement of £2,568 has been, as set forth in the Accounts, to bring up the value of our assets, which figured last year at £59,835, to £62,404, that being the difference between the £101,739 which you see on page 681 of the Accounts against the liabilities of £39,335. The Council have specially incorporated into the Report a reference to these assets, because they think it is proper that every member should be aware of the fact that when we talk of assets of £62,404 we are reckoning the value of the Institution building and lease at the cost price. Obviously we are thereby open to criticism because we have been now in possession for about three years, and there may be those who would say that it would be proper to take into our Accounts a depreciated amount rather than the full amounts which we have paid.

But the Council feel justified in taking in these amounts at the figure which they expended, because of the policy which they have set on foot, and which they feel certain their successors will continue, of paying premiums to the Insurance Society which will enable them, on those policies, to recover at the end of the lease the full amount of their expenditure on the Institution buildings and lease. With these explanations I beg to move the formal resolution, "That the Statement of Accounts and Balance Sheet for 1911 as presented be received and adopted."

Mr. R. K. GRAY: Mr. President and Gentlemen, I have much pleasure in seconding the motion which is before you. What the Honorary Treasurer has told you is, of course, a recital of the facts relating to last year. As the Chairman of the Finance Committee, the only remark that it occurs to me to make, if I may be allowed to make any extra remarks, is this, that while what the Honorary Treasurer said is absolutely correct as to the past, yet if the members present left this building with the impression that that is absolutely the condition of the Institution finances, it would be a mistake that they should carry that away with them. That is to say, the statement which the Treasurer has made is correct in every way, but it is not quite what one would say if one were speaking of the future. I can state without any qualification whatever that the future is all right and sound—let that be perfectly clear, but the £2,500 which some of you may perhaps understand as being perhaps a normal balance of revenue should not be considered so. There have been changes with regard to our tenants. The tenants we have are leaving quite soon—that is, the tenants whose rent has been carried into the revenue account this year, and which has consequently been a help to creating the balance which the Honorary Treasurer has mentioned. We have been able to arrange for new tenants for part of the premises occupied by the tenants who are leaving, but the rent we shall receive from those new tenants will not affect the balance so favourably at the end of this year. I do not want to depress you in any way, but I think it is only right you should not leave the building with the impression in your mind that we have a normal balance of £2,500 a year. The Accounts for next year will be all right, but they probably will not show the same balance as is shown this year. I mention that especially in regard to the fact that the Council has thought fit to raise the subscriptions, while, from the statement of the Honorary Treasurer, it might appear to some that if the Institution is being carried on in such a way that there is a balance of £2,500 on the revenue account at the end of the year it would seem rather an extraordinary thing to have to raise the subscription. It really is a necessity for the Institution to have this extra money, and while the Accounts are all right for last year, I think there should be no misunderstanding in your minds that the increases of subscriptions are absolutely necessary for the welfare of the Institution. With these remarks, which are purely explanatory, I have much pleasure in seconding the motion.

The PRESIDENT: Now that the Accounts have been duly proposed and seconded, I would ask any member who wishes to make any remark on the subject, or has any questions to ask, kindly to do so now.

Mr. W. C. P. TAPPER: With reference to the Tothill Street property, I notice that the interest on the Tothill Street property for the year is £488 15s., whereas the total revenue is £96 2s. 11d. I am not quite sure whether I am correct in the way I read that, but apparently the Institution are losing a considerable sum per annum on that property. I do not know whether the Council have considered the question of disposing of it, because if the loss is £392 per annum—that is the amount which I estimate it at—the Institution could even afford to lose a little money on capital to save that annual amount. I throw that out as a suggestion. I am not criticising the figures in any way.

Mr. C. W. S. CRAWLEY: I should like to ask how the value of the Tothill Street property is obtained. What we actually get from it appears to be ½ per cent. per annum, which is rather a poor return. It sounds as if it was considerably over-valued.

Mr. R. HAMMOND: I am grateful to those who have raised the point with regard to the Tothill Street property, because it enables me to give what I think is a much needed explanation, which I did not venture to deal with in my remarks, because I was anxious to keep them within the prescribed ten minutes. The position with regard to Tothill Street is this. We bought that property, as many present will remember, with the view of building upon it, but we found that it was very difficult indeed to acquire the neighbouring site, which alone would have made it useful, and consequently it has been left on our hands. We obviously now do not want the Tothill Street site any longer, and we shall be very glad indeed to sell it; but that prevents us granting long leases, because, if we granted leases in the ordinary commercial way, we should never be able to sell, because nobody would be able to get free possession. At the moment, therefore, the Council feel that they had much better sacrifice a considerable portion of the revenue from Tothill Street in order to enable them to be in the market in case a buyer came along. I may say, with regard to Mr. Tapper's inquiry, that the question of the disposal of the Tothill Street property is one which the Council have very seriously before them, but they find themselves in somewhat of a dilemma. If they were to abandon the idea of selling, they would then be able to let it, as they let it before, for close upon £1,000 a year, yielding a net annual revenue of about £700. As long as they feel they ought to be ready to sell, they are giving such short leases that tenants are not forthcoming. That, I think, replies to the last query. With regard to Mr. Tapper's remark, that the Tothill Street property cost us £488 a year, there is a little misapprehension. The Tothill Street property cost us £351, and the rent from the tenants last year was only £447, though of course it was much nearer £1,000 in former years. That leaves us a net return—you cannot call it a profit—of £96 on the Tothill Street property. As a matter of fact, when we came here we

had to borrow, and we used the Tothill Street property as one of our securities. Mr. Tapper has drawn attention to the fact that the interest on the mortgage in respect of the Tothill Street property amounts to £488. Obviously that must not be debited against the Tothill Street property; that can be more properly debited against this building, because that was one of the securities which we deposited with the insurance society in order to enable us to complete the purchase here. With reference to Mr. Robert Gray's remarks, I would like to say this, that it is absolutely true that these Accounts show £2,500 to the good, and that as long as the upper part of this building continued to be let they would continue to show that amount. At the present time an important change has been made, and I thought that Mr. Gray was going to encourage you by saying that, in spite of the Medical Colleges leaving us, they were being succeeded, as to a good proportion of the premises, by so eminent a body as the London County Council. But he did not even allow himself that grain of comfort. Mr. Gray also said, that if we were to continue that £2,500 to the good, why raise the subscriptions? Well, my reply to that is this: that we desire to get out of debt. I shall never be satisfied until all this mortgage business is put an end to, and therefore, if by means of getting a revenue to the full from the upstairs premises we could continue with our £2,500 a year to the good, I am able to assure you that both the Chairman of the Finance Committee and the Honorary Treasurer for the time being would find a most useful purpose for the extra money in reduction of debt, though what we are looking forward to in the increase of subscriptions is not so much relief in the finances of the Institution, but to enable us considerably to increase its work and scope.

The PRESIDENT: I will now put the motion: "That the Statement of Accounts and Balance Sheet for 1911, as presented, be received and adopted."

The resolution was put, and carried unanimously.

Mr. J. E. KINGSBURY: The resolution which I have the pleasure of proposing is: "That the best thanks of the Institution be given to the Honorary Secretaries of the Local Sections and the local Honorary Secretaries and Treasurers abroad for their kind services during the past year." I desire to put that resolution to the members in something more than a formal manner. The services which are rendered by the Honorary Secretaries we on the Council know from the regular day-to-day work. But, as some of you perhaps are aware, some of the Members of Council have had the opportunity of coming in somewhat closer contact with the Local Sections than is customary. Your President has done a great deal of travelling on that account, and some of us have also done a little. In that capacity I can say that in the past few months I have had a great opportunity of realising the amount of work, attention, and zeal which is devoted to the interests of the Institution by the Honorary Secretaries. I therefore, sir, with that experience in mind desire to submit this resolution to the members with all heartiness.

Mr. W. M. MORDEY: I have much pleasure in seconding that resolution.

The resolution was put and carried unanimously.

Mr. H. HIRST: "I have much pleasure in moving: "That the best thanks of the Institution be given to Mr. Robert Hammond, in recognition of the valuable services rendered by him as Honorary Treasurer of the Institution during the past year." I do not think the amount of work that has to be done in the important office of Treasurer of the Institution is sufficiently appreciated. Our operations are growing from year to year, and it requires both the mind of a financier as well as the active and detailed work of a hard-working man to keep pace with the work that has to be done. I am sure it is little known amongst the great majority of members, though it is much appreciated by the Members of Council, how untiring and zealous Mr. Hammond is in the performance of his work. I think he is the most regular attendant at our Council and Committee meetings; he never fails to impart to us the great knowledge he has of the affairs of the Institution for the benefit of all the Members of the Council, and he has such a grasp of the Accounts that it will be difficult for us to find a successor for him. I hope that day will be long distant. With these words I move the resolution which I have just read.

Mr. A. A. CAMPBELL SWINTON: I have much pleasure in seconding the resolution. I do not think after what Mr. Hirst has said I need say any more, but I would like to say how heartily I agree with the remarks Mr. Hirst has made with reference to Mr. Hammond.

The resolution was then put and carried with acclamation.

Mr. W. H. PATCHELL: Mr. President and Gentlemen, the resolution which has been put in my hands is in reference to the Honorary Auditors. Mr. Alabaster and Mr. Sidney Sharp have served us for many years, and our warm thanks are due to them for that service. I beg to propose: "That the best thanks of the Institution be accorded to the Honorary Auditors, Mr. H. Alabaster and Mr. Sidney Sharp, for their kind services during the last year."

Mr. JUDD: I have great pleasure in seconding the resolution which has been proposed by Mr. Patchell.

The resolution was put and carried unanimously.

Mr. B. M. JENKIN: I have much pleasure in proposing the following resolution: "That the best thanks of the Institution be tendered to Messrs. Bristows, Cooke, and Carpmael for their kind services in the capacity of Honorary Solicitors to the Institution during the past year. I would like to remind you, Gentlemen, that there has been a very considerable amount of work to do in connection with the revised Articles, and I think our thanks are specially due to these gentlemen on that account.

Mr. R. K. GRAY: I have very much pleasure in seconding that.

The resolution was carried unanimously.

The PRESIDENT: I have to propose "That Mr. H. Alabaster and Mr. Sidney Sharp be elected Honorary Auditors for the year 1912–13."

The resolution was put and carried unanimously.

The PRESIDENT: I have to report with regard to the offices of President, Vice-Presidents, Honorary Treasurer, and Members of Council, that no nominations having been received for these offices other than those announced at the Ordinary General Meeting of the 18th April, 1912, the Council's nominees are, in accordance with Article 45 of the Articles of Association, duly elected to their respective offices. I have to announce that the scrutineers of the ballot for the election of an Associate Member of Council report Mr. A. B. Anderson to be duly elected. The Council for the year 1912–13 will therefore be constituted as follows:—

President.

W. DUDDELL, F.R.S.

Vice-Presidents.

W. JUDD.
C. H. MERZ.
MAJOR W. A. J. O'MEARA, C.M.G.
J. F. C. SNELL.

Honorary Treasurer.

ROBERT HAMMOND.

Members of Council.

H. DICKINSON.
F. GILL.
J. S. HIGHFIELD.
H. HIRST.
B. M. JENKIN.
J. E. KINGSBURY.
P. V. MCMAHON.
R. K. MORCOM.
S. L. PEARCE.
H. FARADAY PROCTOR.
A. RUSSELL, D.SC.
W. RUTHERFORD.
A. H. SEABROOK.
ROGER T. SMITH.
C. P. SPARKS.

Associate Members of Council.

A. B. ANDERSON.
S. MORSE.
H. E. WIMPERIS.

PRESENTATION OF THE KELVIN BUST.

The PRESIDENT: I will now call upon Sir William Preece to make the presentation of a bust of the late Lord Kelvin.

Sir WILLIAM PREECE: Mr. President, Ladies and Gentlemen, to-night I am going to discharge a difficult and a very arduous task. It is my duty, on behalf of Lady Kelvin, to present to this Institution a bust of our great Past-President, Lord Kelvin. I am probably the oldest living electrical friend of his, for I first met him in the year 1853, nearly sixty years ago; and I have no doubt that that has weighed with Lady Kelvin in asking me to undertake such a very important and difficult task. Whether we regard Lord Kelvin as a

student, a thinker, a philosopher, a teacher, an engineer, a sailor, or a Christian, we find that he has left no duty undone, and the World, the Crown, Parliament, the Press, the Learned Societies, Universities and Schools have responded by leaving no honour unbestowed upon him. He was three times our President. I hope that your President and Council will gratefully accept this admirable, expressive, and also almost living representation of him whom many of us loved so well. It will be a permanent memorial of one who always, if he could, instructed from models, and who thus can become a model himself to all future electrical engineers to follow and to emulate. Longfellow wrote :—

"Life is real, life is earnest,
And the grave is not its goal;
Dust thou art, to dust returnest,
Was not spoken of the soul."

Nor was it spoken of the mind. Kelvin's mind will ever be with us, for his works are classic, and his conclusions immortal. Few men have had their lives more splendidly written for our guidance. His early home life, written by his departed sister, Mrs. King, has been edited by her daughter and his niece, Miss Elizabeth Thomson-King, in a charming and fascinating book "Lord Kelvin's Early Home." Professor Silvanus Thompson has given us his life in a biography that deserves to rank second only to Boswell's "Life of Johnson." It not only narrates the historical career of the man, but it details the scientific and experimental growth of his doctrines and inventions in language so simple and so plain that "he may run that readeth it."

Our great heroes, the founders of practical science, are Newton, Faraday, and Kelvin. Kelvin will now be before you. I shall not be happy until I see him accompanied by my earlier master, Faraday, and if I am spared I shall hope to be in a position to present to the Institution a bust of Faraday that shall be a match to the bust of Kelvin.

An important question will arise, which we, of course, will leave in the hands of the President and Council, and that is the position of this bust, and, I hope, its companion. It has almost been solved for us, because you find on each side of this table the name of Kelvin and the name of Faraday, and it seems almost providential that those marks should indicate that they should go there. But there is this difficulty: diagrams might be interfered with by the presence of these two busts. On the other hand, in the Hall—the very fine, handsome, marble hall we have—there are two pedestals planted there evidently with the idea of supporting our two greatest heroes. Here they are, Faraday and Kelvin. But we do not ask you to adopt any position, Mr. President; we leave it to your judgment and to your care.

Now in the name of his faithful companion, sympathetic helpmeet, and afflicted widow, I present to the President and Council of the Institution of Electrical Engineers this remarkable bust, the work of Mr. McFadden Shannan, of Glasgow, who deserves all the praise we

can give him for preserving for us the features of him who was not only our leader, but our guide, our philosopher, and our friend.

In the name of Lady Kelvin, Mr. President, I present to you and to the Institution the beautiful bust which you see before you.

Professor SILVANUS THOMPSON : Mr. President : Our senior Past-President, Sir William Preece, whom we are so glad to welcome back after his serious illness, has spoken so well and sympathetically of the work that Kelvin did in the wide world and for this Institution that there remains little to be said. But I have been asked by Lady Kelvin to express to you, sir, and to the meeting of the Institution how very sorry she is that, in her state of health, she is not able to be present or to endure the fatigue of this occasion. Lady Kelvin hopes, however, to take a very early opportunity of coming quietly to the Institution to see the bust that she has presented to us. But though we are deprived by circumstances of the presence of Lady Kelvin to-night, we are happy to recognise the fact that the family of Lord Kelvin is not unrepresented here, and I may be pardoned if I mention to those who are present that we have with us two nephews of Lord Kelvin, Mr. James Thomson and Mr. Frank Bottomley; we also have present a sister of Lady Kelvin, Lady Hargreaves Brown and her husband Sir Alexander Hargreaves Brown, Mr. Walter Hargreaves Brown, and Mrs. Forbes, a niece of Lady Kelvin. We thank them for coming here on this occasion, and we are glad that they should see how we appreciate and value this bust, reminding us as it does of Lord Kelvin, who was among us on so many famous occasions in the past. The sculptor, Mr. Shannan, has produced in this bust a very faithful picture of Lord Kelvin. He has already in time past, and when Lord Kelvin was living, executed two other busts of Lord Kelvin. He knew him well, stayed with him at his residence at Largs, and had every opportunity of acquainting himself personally with the features and the expression of him whom we commemorate. Those two busts are one at Netherhall, and the other in the rooms of the Royal Philosophical Society of Glasgow; but I venture to say that Mr. Shannan's third bust, which is now our property, is an exceptionally fine one. We have so recently—it is only three weeks ago—listened in this room to the third Kelvin lecture given by Professor Du Bois, one of Lord Kelvin's numerous disciples, and have heard commemorated in it some of his most notable achievements, that there is no need to emphasise that part of Lord Kelvin's career; but it has seemed to me not inappropriate that one feature should be alluded to. Great, supremely great, as Lord Kelvin was as a mathematical physicist, wielding unrivalled ability in the management of mathematical symbols and in the expression and extension of mathematical ideas, he nevertheless through all his career had the closest touch with physics and with the commercial applications of physics. He has left it emphatically on record that he did not take that somewhat supercilious attitude which some great mathematical physicists have taken—that all these commercial applications were to be set aside as unimportant compared with abstract science. Not so Lord Kelvin. He has left on record that he thought

the very life and soul of science lay in the use to which it was put for the service of mankind, and that abstract science was indebted again and again to its useful applications for the impulse that had been given to it and for the resources which had developed it. Of that he was himself the most conspicuous example, for, as we know, his many researches into the properties of electricity and the important contributions that he made to the physical laws of electricity, no less than his practical contributions of which Professor Du Bois spoke in the designing and constructing of instruments and apparatus for the further study of electricity, show how Lord Kelvin was in sympathy with both aspects of that which is the object of this Institution, the cultivation of electricity and of its applications. And now that we have this permanent record to put among the busts that belong to this Institution we shall feel that we have a perpetual reminder of the presence of the man himself. Those of us who have had the privilege of knowing him and sitting at his feet will see there a very worthy presentation of him which again and again will remind us of the days when he was with us in the flesh; while those who never had that privilege will equally know from the faithful presentment here what manner of man that was who made so great, so deep, so lasting a record upon the science of his time, and on one of the greatest of British industries. I ought perhaps to mention that we not only are in possession of this bust of Lord Kelvin, and of the promise of a bust of Faraday to stand beside it in years to come, but we have a number of other similar memorials of the great men of the past. We possess an exceedingly fine bust of Volta, presented to us by the Italian Association of Electricians; we possess a bust of Benjamin Franklin, similarly sent to us by the American Institute; we have a bust of our lamented former President, Dr. Hopkinson; we have also busts of Sir Francis Ronalds, whose library we rejoice in possessing here; of Sir Charles Bright, whose name will ever be remembered in connection with the early cable enterprise; and we have also an excellent medallion of our founder, General Webber. These are not unworthy companions of the bust of Lord Kelvin which has just been presented to us. I am sure that if Lady Kelvin could have been here to-night she would have rejoiced to know how much we appreciate the additional possession which now is ours, and which we shall treasure for years to come.

Mr. JAMES THOMSON: Mr. President, Ladies, and Gentlemen, it was with very great pleasure that I came to London to-day to have the opportunity of seeing this very beautiful bust of my late uncle. It is a very fine likeness—it is really a speaking likeness, and I can only say that I wish to congratulate Mr. Shannan, the artist, very heartily on his achievement. It is a great gratification, I am sure, to all of Lord Kelvin's relations to think that this bust is in the keeping of this Institution of which I believe he was among the founders—I think I am right in saying so. I am sorry to say I am not an electrical engineer, but speaking as one who, as an outsider, takes a great interest in electrical knowledge, I shall be very glad indeed if, through the instrumentality

of Sir William Preece, a companion bust of Faraday can be placed in this Institution's rooms alongside the bust of my uncle. Sir William Preece and Dr. Silvanus Thompson have spoken very feelingly about my late uncle's work, and therefore I am sure you will excuse me for not saying anything further. I only wish to add that I have seen Lady Kelvin this evening, and she is very sorry that circumstances prevent her from being here to-night. She would have liked to be present had she been able to do so.

The PRESIDENT : I now have the great pleasure of accepting, on behalf of the Institution, its Council and its membership, the bust of Lord Kelvin which has been presented to us, through the instrumentality of Sir William Preece, by Lady Kelvin. I can only say one word about this, and that is that we receive this bust with the most profound thankfulness.

A paper by Mr. A. W. Ashton, Associate Member, entitled "Condensers in Series with Metal filament Lamps" (see page 703), was read and discussed.

CONDENSERS IN SERIES WITH METAL FILAMENT LAMPS.

By A. W. ASHTON, Associate Member.

(*Paper received 2nd March, received in final form 9th April, and read before* THE INSTITUTION *16th May*, 1912.)

The object of this paper is to describe certain developments which have recently taken place in connection with the running of low-voltage metal filament lamps in series with condensers on alternate-current circuits. An account is given of an important improvement in the process of manufacturing paraffin-paper condensers, which has made the condenser much more suitable for use on ordinary lighting circuits. A method of running a variable number of lamps in series with a single condenser is described, and the "current limiting" property of the condenser when used in this way is discussed. Certain advantages of the condenser in preventing "overshoot" when switching on metal filament lamps and in cheapening the wiring of small houses are dealt with, and the effect on the power factor of public supply systems caused by the extensive use of condensers is also considered

INTRODUCTION.

The use of condensers on alternating-current circuits has been fully discussed by Mr. Mordey in a paper * read before this Institution, in which a comparison is made between the costs of condensers and of synchronous motors when used for the compensation of lagging currents and the consequent improvement of power factor. In this paper it is shown that with regard to both initial and running costs, paraffin-paper condensers are more economical than synchronous motors, and the opinion is expressed that the use of these condensers "is now within the region of practical engineering."

In adopting condensers for running low-voltage metal filament lamps on alternating-current circuits of higher voltage, the question of improvement in the power factor of the whole circuit, although merely, as it were, incidental in this case, should not be lost sight of; for example, it would no doubt prove more advantageous to the supply authority actually to fix condensers on consumers circuits free of charge than to run synchronous motors for the same purpose. It is also obvious that a consumer taking a leading current, and thus in a good many cases acting as a negative load on the system, should not

* *Journal of the Institution of Electrical Engineers*, vol. 43, p. 618, 1909.

be debited with the same proportion of capital cost as an ordinary lighting consumer, and that to such a consumer a lower charge per unit might with advantage be made. Where, however, the full efficiency of the tungsten filament is obtained, *i.e.*, by the use of the proper methods of illumination, and by a system in which the consumer is not compelled to use higher candle-powers than are really necessary, the cost of energy becomes of less importance than the initial cost of wiring and that of lamp renewals. With energy at 3d. per unit a 10-watt lamp could be run for 1,300 hours for an amount equal to the initial cost of the 20-watt 200-volt lamp. In the case of small houses the cost of wiring and of lamp renewals becomes of increasing importance, and it is in this direction that the use of condensers appears specially advantageous.

IMPROVEMENTS IN THE MANUFACTURE OF PARAFFIN-PAPER CONDENSERS.

The condensers which have been employed in connection with metal filament lamps have been of the Mansbridge type, consisting of tinfoil paper impregnated with paraffin, the impregnation being carried out by a new process, which is the invention of Mr. E. A. Bayles of the British Insulated and Helsby Cables, Ltd.

The manufacture of condensers from tinfoil paper and the method of "breaking down" the weak spots in the paper by vaporising the tinfoil in the neighbourhood of the fault have been fully described in a paper* read before this Institution by Mr. G. F. Mansbridge.

Prior to the introduction of the improved impregnating process it was the practice to carry out the paraffin wax impregnation under vacuum. The condensers manufactured by this process have been found thoroughly satisfactory for telephone circuits, and certain other purposes for which they have been largely used.

In testing a large number of such condensers with alternating pressure it was found that breakdowns always occurred along a certain curve, viz., that connecting points of equal temperature in the wax while cooling after impregnation. This pointed to the possibility of the dielectric becoming weakened electrically due to shrinkage in cooling, and to the fact that the interstices between the layers of paper and tinfoil were not compl tely filled with paraffin. This drawback is obviated by the new process, the interstices being completely filled with paraffin, which results in the dielectric strength of a condenser of given thickness of paper being practically doubled.

The new process consists essentially in the immersion of the condenser roll in melted paraffin wax after vacuum impregnation, and the subjection of the wax to high mechanical pressure during the process of cooling. This pressure is about 1 or 2 tons per square inch, and it is important to note that while the pressure is maintained on the paraffin, the condenser itself is not pressed upon in such a manner

* *Journal of the Institution of Electrical Engineers*, vol. 41, p. 535, 1908

as will flatten or otherwise distort its shape. The pressure is maintained until the paraffin is cooled and set.

The superiority of the condensers produced by this process compared with paraffin condensers hitherto produced is most marked, particularly with regard to dielectric strength and reliability when working on alternating-current circuits; the recent developments in the use of condensers have been largely due to the introduction of this process.

Dielectric Losses.

A series of tests for the determination of the dielectric losses in condensers manufactured by the new process have been made by the author in the electrical engineering laboratories at Battersea Polytechnic.

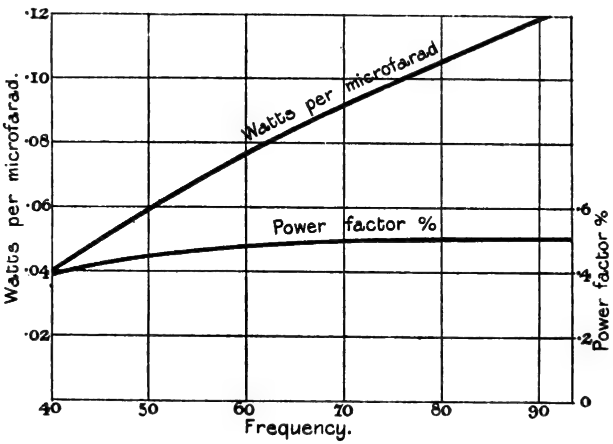


Fig. 1.—Dielectric Losses in 15-microfarad Condenser at 200 Volts.

The losses were measured by means of a quadrant electrometer, the needle being charged with half the voltage on the circuit in order to avoid the correction for energy loss in the current resistance. The method is substantially that described by Mr. E. H. Rayner in a paper recently read before this Institution.* The importance of eliminating the above correction is evidenced by the fact that in some cases where the losses did not exceed 1 watt the current resistance absorbed about 60 watts.

The curves given in Figs. 1 and 2 show the results obtained for a 15-microfarad condenser suitable for pressures up to 250 volts. In each case the losses are expressed in watts per microfarad, and also as percentage power factor.

In obtaining the results shown in Fig. 1, the voltage on the con-

* *Journal of the Institution of Electrical Engineers*, vol. 49, p. 3, 1912.

denser was kept constant at 200, and the frequency was varied from about 40 ∿ to 100 ∿.

The loss is very nearly proportional to the frequency within these limits, the power factor only increasing 25 per cent. when the frequency increases from 40 ∿ to 100 ∿.

In Fig. 2 the results of tests on the same condenser at different voltages from 80 to 240, and a constant frequency of 50 ∿ are given. The loss increases with the voltage, and the power factor is considerably lower at the higher voltages, being as low as 0·38 per cent. at 240 volts, and increasing to 1·3 at 80 volts.

At 200 volts 50 ∿ the power factor is 0·44 per cent., corresponding to a total loss of 0·85 watts for the 15-microfarad condenser. The overall dimensions of this condenser are 5¼ in. × 5¼ in. × 4¾ in., giving a total external surface of 160 sq. in., from which it is obvious that the

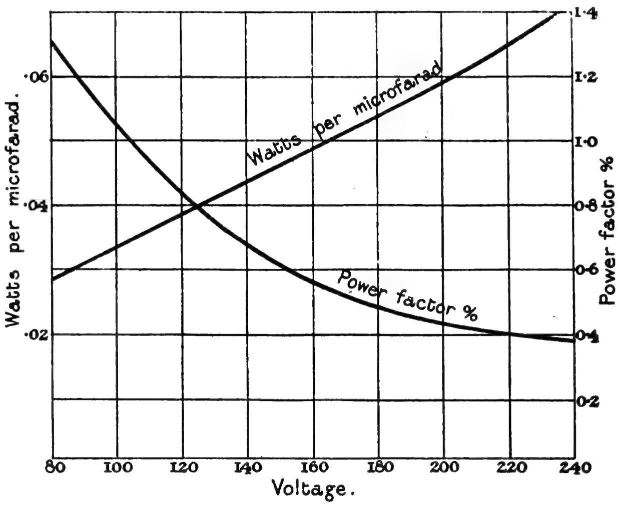


FIG. 2.—Dielectric Losses in 15-microfarad Condenser at a Frequency of 50 ∿.

temperature rise is absolutely negligible. When this condenser is fully loaded, the lamps will aggregate from 80 to 90 watts, so that the efficiency is about 99 per cent. at full load. If this condenser is left continuously on a supply circuit it absorbs energy at the rate of about 7 units per annum. Thus from every point of view the condenser is a highly efficient piece of apparatus, and owing to its small losses and negligible temperature rise it is practically impossible for it to deteriorate in use.

USE OF CONDENSERS IN SERIES WITH METAL FILAMENT LAMPS.

The author's attention was first directed to this question in December, 1909, in connection with the application of condensers to improve

the power factor of transformers running single-arc lamps on a 430-volt circuit. The successful use of condensers in this case drew attention to the possibility of displacing transformers by condensers both for arc and incandescent lighting. In the former case, however, it will generally be found that it is cheaper to install a transformer ; besides which the operation of the arc in series with the condenser is not quite satisfactory, chiefly owing to the fact that with the carbons touching, the current is not much greater than the normal, and therefore the arc is not struck quickly enough.

On the other hand, it is found that for incandescent lighting the condenser possesses certain valuable features, which, combined with its moderate cost, makes it suitable for use in conjunction with low-voltage lamps where otherwise either high-voltage lamps would be used or an auto-transformer installed.

It is not the intention of the author to discuss the comparative advantages of low-voltage and high-voltage lamps except to point out that apart from the higher efficiency and longer life of the low-voltage lamp the latter is considerably cheaper to manufacture, and has an infinitely more robust filament. Further, when one considers the fact that the initial cost of a condenser for a single lamp is often not more than twice the cost of the lamp, it is evident that the prevention of one or two accidental breakages will easily cover the cost of the condenser.

For convenience in dealing with the application of condensers in series with incandescent lamps, we may divide the various methods into two groups :—

1. The ordinary or parallel system, in which each circuit consists of either a single lamp or a number of lamps in series with a condenser and controlled by a single switch. In this method the lamps must all be used at once, and the aggregate of the voltages of the lamps in series may be as much as 90 per cent. of the supply voltage.
2. The series system, in which each circuit consists of a number of lamps all in series with each other and with the condenser, and controlled by short-circuiting switches in parallel with the lamps. The aggregate of the voltages of the lamps installed may be about 60 per cent. of the supply voltage, but the aggregate voltage of lamps used simultaneously should not be more than 35 to 40 per cent. of the supply voltage. Subject to this limit any number of lamps may be used simultaneously.

The Parallel System.

This system necessitates the use of a condenser corresponding to each switch, as owing to the "constant current" property of the condenser the number of lamps connected in parallel must be constant.

The size of the condenser must be determined with reference to

both voltage and current of lamp, as well as the supply voltage and frequency. The capacity required is given by—

$$K = \frac{C \times 10^6}{2\pi \sim \sqrt{V_1^2 - V_2^2}}$$

where—

K = capacity in microfarads.
C = rated current of lamp.
$\sim$ = supply frequency.
V_1 = supply voltage.
V_2 = lamp voltage.

The capacity required is therefore directly proportional to the lamp current, and inversely proportional to the frequency and to the vec-

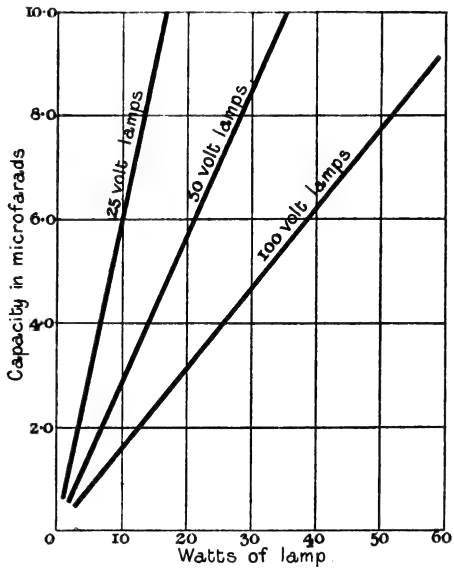


FIG. 3.—Capacity of Condenser for a given Voltage and Wattage on 220-volt 50-$\sim$ Circuits.

torial difference between supply and lamp voltages. Generally speaking, the application of condensers is limited to supply voltages of 200 or more at 50 $\sim$, except for comparatively low candle-power lamps (up to 10 watts). At frequencies of 70 to 100, however, the cost of condensers for running 50-volt lamps on 110-volt circuits comes out reasonably low even in the case of 28-watt lamps.

The capacities required for different lamp voltages are shown in Figs. 3 and 4, from which some idea of the size of the condenser for any given lamp can be obtained. The capacity is inversely propor-

tional to the supply voltage in the neighbourhood of 220 volts, *i.e.*, from 200 to 250.

From Fig. 4 it can be seen that when using the parallel system for lamp voltages of less than 25, the cost of the condensers becomes rather excessive; but it must be noted that three 25-volt lamps may be run on the same condenser without appreciably increasing the capacity, and by adopting the series system these need not be all in one room, but can be separately controlled by short-circuiting switches.

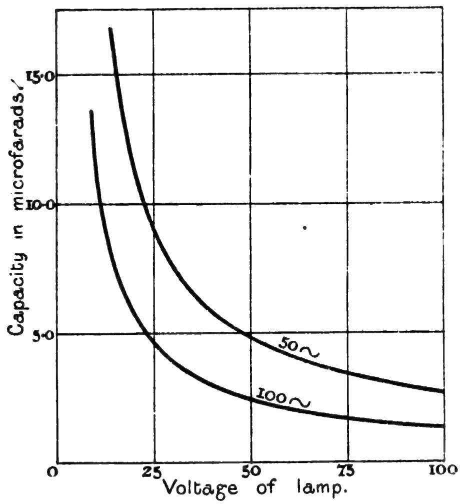


FIG. 4.—Capacity required to run one 14·5-c.p. Tungsten Lamp on a 220-volt Circuit.

The cost of the condensers is not quite proportional to the capacity, but may be represented approximately by the equation :—

$$\text{Cost in shillings} = a + b\ \text{K},$$

where $a = 2{\cdot}0$ and $b = 1{\cdot}5$ for 250-volt condensers of capacity K microfarads.

Owing to the small dimensions, viz., $2\frac{1}{2}$ in. × $2\frac{1}{2}$ in. × 6 in. for the 5-microfarad condenser, and the fact that the condensers work continuously with no appreciable temperature rise, they may be conveniently fixed in any out-of-the-way place, such as under the floor, above the ceiling rose, on the wall near the switches, or by means of an adapter in the actual lampholder.

The adoption of this system implies practically no disturbance of the existing wiring, but it becomes rather expensive in the first cost where the aggregate of voltages of lamps in series with one condenser is low. It is interesting to examine how the requisite capacity for a

given candle-power varies when the total voltage of lamps in series is altered.

It can be shown that the minimum capacity is required when the voltage on the lamp or lamps is 70·7 per cent. of the supply voltage. From Fig. 5 it appears that the minimum capacity is 13 microfarads for running lamps aggregating 100 watts on a 220-volt circuit at 50 ∼. The capacity, however, is not greatly increased if the voltage of the lamps is as low as 100 or as high as 200.

With regard to the flexibility of this system it should be noted that on 200-volt circuits any lamp of a lower voltage than 60 can be replaced by a lamp of different candle-power provided the two lamps have the

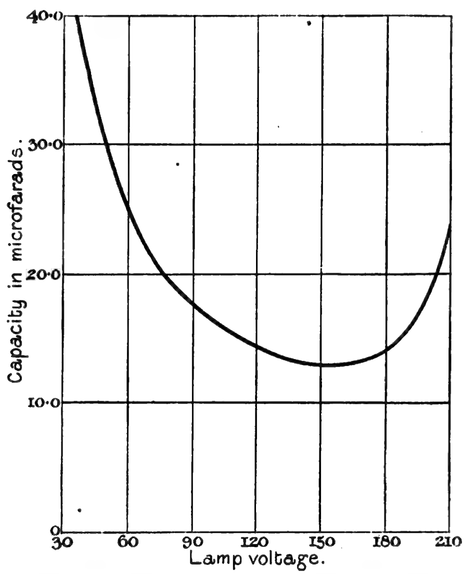


FIG. 5.—Capacity required at different Lamp Voltages for one 100-watt Lamp on a 220-volt 50-∼ Circuit.

same rated current. Thus the same condenser is always suitable for a 5-watt 25-volt lamp and a 10-watt 50-volt lamp; and if the candle-power requires to be still further increased a 17- or 18-watt 100-volt lamp should be used.

The condensers are listed for running 25-, 50-, or 100-volt lamps on circuits of any pressure or frequency met with in practice, and it has been found more convenient to refer to them by using serial numbers instead of the actual capacities.

This system is particularly applicable to the case of houses of moderate size, viz., of less than about 25 lights, and in which the number of points, where less than 25 watts is required, will be about one-third of the total. In these cases condensers would be required

only on the lower candle-power points, and in those positions where the lamps are liable to be handled.

The first cost is less than when an auto-transformer is installed, all "no load" losses are obviated and the running losses are considerably reduced. Compared with the use of high-voltage lamps at all points, there is considerable saving both in the cost of energy and of lamp renewals, amounting in a number of cases to more than 50 per cent. on the assumption of equal life for the high-voltage and low-voltage lamps. When one considers the advantage the condenser possesses in limiting the initial rush of current, and when one compares the fragility of the high-voltage filament for small candle-powers with the comparative strength of the low-voltage filament, it appears very probable that the actual saving will be greater.

The Series System.

The possibility of running a variable number of low-voltage lamps, all having the same rated current, in series with a single condenser and controlled by "short-circuiting" switches, is due to the fact that the vectorial difference between the two quantities in quadrature, when one is much smaller than the other, is very slightly less than the greater of the two quantities. Thus the condenser splits the supply voltage into two components in quadrature, and when the lamp voltage is as much as 30 per cent. of the supply voltage the condenser voltage is only 4·6 per cent. less than the supply voltage. With tungsten filament lamps in series with the condenser the actual reduction in current is less than this due to the decreased resistance of the filament when the current is below normal. The maximum percentage variation can be still further decreased by adjusting the capacity of the condenser to such a value that the lamps get their correct voltage when the aggregate of voltages of the "switched-in" lamps is 25 per cent. of the supply voltage. Under these conditions it is possible to use a variable number of lamps up to 35 or 40 per cent. of the supply voltage without the lamp current deviating more than 3 per cent. from the normal.

In Fig. 6 is given the percentage deviation of lamp current and voltage from the normal for different nominal lamp voltages, the rated current being correct when the lamp voltage is 25 per cent. of the supply voltage. Under these conditions the variation in the candle-power of the lamps is no greater than is given by carbon filament lamps due to ordinary variations in voltage, but in any case the current variation may be made less than 3 per cent. if necessary by keeping below the 35 per cent. of supply voltage, *i.e.*, by adopting lower voltage lamps.

The necessary condition to be followed by the lamps in series with any one condenser is that they should all have the same rated current, the voltage being therefore proportional to the wattage required. Thus for a condenser giving 1 ampere, a 25-watt lamp must be

rated at 25 volts, a 10-watt lamp for 10 volts, etc. With such a condenser the maximum wattage of lamps simultaneously in use on a 220-volt circuit would be about 80, but where, as would generally be the case, all lamps are not required at once, the wattage of lamps installed may be about 120. Any required wattage of lamps can be used in connection with a single condenser by varying the rated current of the lamps, but it will generally be found more convenient to run each group of 10 lamps on a separate condenser.

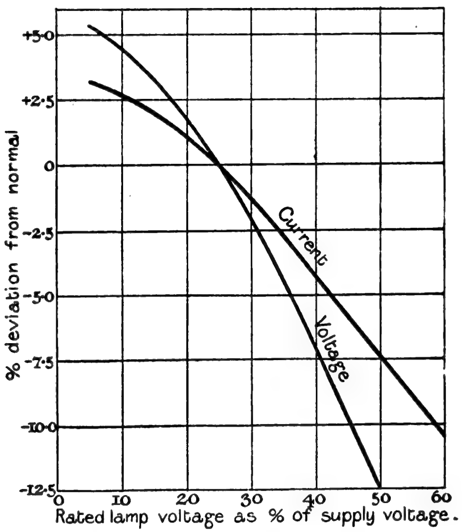


Fig. 6.—Percentage Deviation of Current and Voltage from Normal in the Series System with different Lamp Voltages.

Compared with the parallel system, the chief advantages of the series system are :—

1. Although low-voltage lamps of 10 to 25 volts can be used, the cost of the condenser is only about 2s. 6d. per lamp on 220-volt 50-∿ circuits.
2. The condenser acts as a current limiter and effectually prevents the consumer increasing his maximum demand to any serious extent without the knowledge of the supply authority.
3. By using switch-holders a considerable reduction can be effected in the cost of wiring due to there being only one wire run from ceiling rose to ceiling rose.
4. The electric stress on the insulation of the wiring is considerably reduced, and risk of fire due to "short circuits" occurring is entirely eliminated, due to the fact that the power supplied by the circuit to the fault is limited by the condenser.

The series system is more particularly applicable to small houses or flats not requiring more than about 10 lights and to groups of low candle-power points in larger houses. In the latter case the lamps may be all in one room and divided for convenience in illumination, or the whole of the smaller rooms in a house may be wired in series.

When applied to houses already wired, this system will obviously necessitate certain alterations in the wiring, but a number of points "looped in" can generally be reconnected on the series system without actual interference with the wires themselves, it being only necessary to alter the connections at the ceiling roses and switches. It should be noted that although lamps of 5 watts or even less can be used on the series system, by putting in the condenser as near as possible to the lamps the full pressure is available where required for heating, cooking, etc.

Current-limiting Effect of the Condenser.

The current taken by the condenser is a maximum when all the lamps are short-circuited, and in the series system this will be about 3 per cent. greater than the normal current. It can be further shown that the maximum power taken by the circuit when the number of lamps is increased, corresponds to the condition that the resistance of the lamps (r) is equal to the reactance of the condenser (x).

The power supplied to the circuit (W) is given by—

$$W = \frac{V_1 \, r}{r^2 + x^2},$$

which is obviously a maximum when $r = x$, and under this condition—

$$W_{\text{max.}} = \frac{V_1^2}{2x}.$$

That is $W_{\text{max.}}$ = half the apparent power taken by the condenser when $r = 0$. For a 1-ampere condenser on a 220-volt circuit the maximum power is 110 watts, but the rated voltage of the lamps which must be switched in before this maximum is reached is 20 per cent. greater than the supply voltage, and with lamps whose aggregate voltages is 60 per cent. of the supply voltage, the maximum power is about 100 watts. This property of the series system should be useful where a "contract supply" or a "fixed price" system is adopted, as any unauthorised increase in power is effectually prevented.

A further result of the current-limiting effect of the condenser is the prevention of the excessive rush of current which takes place when metal filament lamps are switched on. There appears to be some doubt as to whether this rush of current is accompanied by an actual increase in the temperature beyond the normal running temperature. J. B. Taylor,* working on an alternate-current circuit, has shown by photographs that such a momentary increase of tempera-

* *Electrical World*, vol. 51, p. 1046, 1908.

ture does occur, and suggests that it may be due to a lag of resistance when the temperature increases at such a rate as is obtained in switching on a lamp. On the other hand, Professor Marchant (apparently using direct current) has been unable to detect any such increase beyond normal temperature.*

The damage to the filament may occur whether the temperature is actually increased or not, and is most likely due to the sudden increase in the temperature of the filament when in contact with the cooler leading-in wires and supports. If any part of the filament takes longer to reach its final temperature than the main portion of the filament takes, it is very probable that an "overshoot" in temperature will occur. In using metal filament lamps in series with condensers the lighting up of a low-voltage lamp is much slower than that of a higher voltage one, and in some cases the temperature of the filament is noticeably lower near the supports immediately after switching on. This undoubtedly also occurs when the condenser is not used, and then will result in a momentary increase in temperature above the normal running temperature of the filament.

Compensation for Lagging Currents.

As the extensive use of condensers will affect the power factor of any system in which they may be adopted, it is advisable to consider this question with special reference to the conditions likely to be met in such a case. This subject has already been dealt with in two very interesting papers read before this Institution. In the first, read by Mr. Miles Walker,† the disadvantageous results of the low power factor associated with lagging currents are pointed out, and the various methods of compensation are discussed. The methods considered in the above paper are:—

(*a*) The use of synchronous motor and rotary converters.
(*b*) The use of condensers.
(*c*) The use of "phase advancers" on individual induction motors.

The second paper, by Mr. Mordey,‡ dealt more particularly with the use of condensers for producing the required compensation.

If condensers are used with lamps in order to improve the power factor, it is possible that at certain loads a leading current may be taken by the whole system, and it is interesting to compare this case with that of the lagging currents now generally occurring.

It is convenient for this purpose to divide the effects of wattless currents into two groups:—

1. Those independent of the lag or lead of current.
2. Those operating differently according to whether the "wattless" current is lagging or leading.

* *Electrician*, vol. 68, p. 642, 1912.
† *Journal of the Institution of Electrical Engineers*, vol. 42, p. 599, 1909.
‡ Ibid., vol. 43, p. 618, 1909.

The former group includes C^2R losses in armatures of generators and in mains and transformers, all of which are inversely proportional to the square of the power factor and operate with equal disadvantage whether the current lags or leads. Further in the case of mains or transformers these losses act as a limit to the possible output, while this is not the case with alternator armatures.

The second group includes C^2R loss in fields of generators, and pressure drop in alternators and transformers. The drop in underground mains will generally come into the first group owing to the reactance of the conductors being small, whilst on the other hand overhead mains will generally come into the second group.

While it would be preferable as far as losses are concerned to work with unity power factor, a leading current of a power factor of, say, 0·9 would offer considerable advantages as far as overloads on the generators are concerned.

In the above-mentioned paper Mr. Miles Walker states that having regard to the capacity of the field magnet only, the output of a turbo-generator at unity power factor is four times as great as at 0·8 power factor lagging. Messrs. Macfarlane and Burge have also shown that for a given speed and d^2l (where d = diameter of armature and l = length of core) the output of standard alternators could be doubled if the regulation were not a limiting factor.*

These considerations show that the best conditions could be obtained, not with unity power factor, but with a leading current which, although increasing the copper loss in armature, line and transformers would decrease it in the generator fields, admitting of considerable overloads in the case of existing generators or decreased cost in the case of new generators.

Whatever method of compensation is adopted the units should be distributed more or less uniformly over the system. The use of over-excited synchronous motors, while satisfactory for the generator, does not affect the losses in mains and transformers.

Phase advancers appear to be satisfactory in the case of individual induction motors, but the adoption of these does not generally lie in the hands of the supply engineer, to whom the improvement of power factor more particularly appeals.

The use of the series condenser system in which the condenser is generally in circuit will effectually compensate for lagging currents provided—

1. The condensers are located near the apparatus taking lagging currents.
2. The condensers are in the circuit mainly for the same periods as those in which lagging currents appear.

Though these conditions are not fulfilled in residential districts, yet for the smaller class of property in industrial districts the compensation

* *Journal of the Institution of Electrical Engineers*, vol. 42, p. 232, 1908.

would be found to be satisfactory, having regard to the fact that over-compensation is an advantage as far as the generators are concerned.

With regard to purely residential districts the power factor is generally very high, especially where the district is fed through long cables.

In this connection it must be remembered that practically all cooking apparatus and a large proportion of heating apparatus is inductive to a certain extent; therefore even in these cases if any considerable load is taken for purposes other than lighting the condensers will be an advantage rather than otherwise.

Cost of Wiring on the Series System.

The following is a comparative estimate of the cost of wiring a six-roomed house with 10 points—

1. On the ordinary "loop-in" system using 200 volt lamps.
2. On the series condenser system using switch-holders.

The estimate is on exactly the same basis for each system, viz., for a plastered house and using 600-megohm cable of English manufacture, in enamelled close-joint steel tubing with slip-socket fittings. The prices include wiring contractor's profit, and labour taken at 1s. 6d. per hour for wireman and mate. The cost of the condenser is not included in (2) as it is assumed that this would be balanced approximately by the cost of a current limiter for system (1).

	(1)			(2)		
	£	s.	d.	£	s.	d.
Cable and conduit	1	17	6	1	2	6
Labour on cable and conduit	2	10	0	1	6	4
Pendants, switches, main-switch, and fuses, including labour	2	9	2	2	2	6
Lamps	1	10	0	0	15	0
Total	8	6	8	5	6	4

These estimates show a saving of 38 per cent. by using the series system, and this has been effected in labour and material due chiefly to the reduction of cable from 17 yards to 8 yards per point, and a corresponding saving in labour, conduit, and fittings. The prices are for wiring a single house in each case; they would, of course, be considerably lower where a number of houses could be wired at the same time.

Use of Meters in Connection with the Series System.

Whenever lamps are used in series with a condenser the power factor is given as the ratio of the voltage on the lamps to the supply voltage. It is obvious that in the case of a single 10-volt lamp on a 200-volt circuit the power factor will be 0·05. Since the standard types of meter have not been designed for use on such low power factors, it is an interesting point to consider how far they may be relied on to start and to register accurately in such cases.

The curves in Fig. 7 show the results obtained on a 5-ampere 100-volt induction-type watt-hour meter, which was tested against a sensitive precision wattmeter of the deflexional type. The readings were taken with voltage, current, and frequency constant, the power factor being varied from 0·04 lagging to 0·04 leading, *i.e.*, with a minimum load of 6 watts or 1·2 per cent. of full load.

The results show that this meter is remarkably accurate at low power factors and as adjusted, *i.e.*, reading nearly 1 per cent. high for a current of 3 amperes at unity power factor it is more accurate with leading than with lagging currents. With a power factor as low as 0·08 (leading) the meter reads only 2 per cent. low, but reads nearly 5 per cent. low when the power factor is reduced to 0·04.

This type of meter would appear to read sufficiently accurately in connection with the series system, and could be adjusted so as not to register with the condenser alone in circuit, and to start with certainty when the smallest lamp is switched in. The question, however, arises as to whether it is possible to obviate the losses in the shunt coils of watt-hour meters, which for small consumers form a considerable proportion of the total units supplied.

If the shunt coil of the meter is connected across the lamps alone, *i.e.*, so as to exclude the condenser, the greater part of the shunt loss is obviated, the meter being used at constant current and variable voltage. The dotted curve in Fig. 7 shows the percentage error in the meter mentioned above when used in this way, the power factors being those obtained when using the lamps through a condenser on a 200-volt circuit. Thus for a power factor of 0·1 the lamp voltages would amount to 20. Used in this manner the meter is not so accurate as when the voltage is constant and the power factor varied. Although with 20 volts on the lamps the meter reads only 3 per cent. low, the error rapidly increases when the voltage falls below this.

Since in the series system the current is constant, a volt-hour meter connected across the lamps would accurately register the energy used in the lamps and would reduce the meter losses to a minimum. Such a meter might be constructed on similar lines to the induction-type watt-hour meter by leaving out the series coils and using only "shaded" poles with a shunt winding.

Relays for Automatically Short-circuiting Faulty Lamps.

Where a number of lamps are run in series one disadvantage is that in the event of one lamp failing all the others go out. In the case of

the series system a cheap type of relay can be adopted which will automatically short circuit any lamp thus failing.

Simple series relays would not discriminate between the faulty lamp and others in series. A relay in parallel with each lamp would operate only in case of the faulty lamp, and could be arranged to trip the short-circuiting switch mechanically.

Another possible method is that in which a differentially wound relay is used, which is magnetically balanced when the lamp voltage is applied to one winding and the lamp current sent through the other, the relay contacts being arranged to short-circuit the lamp. When a filament breaks, the shunt coil of the relay gets a considerably higher voltage across it and effectually short-circuits the faulty lamp, the

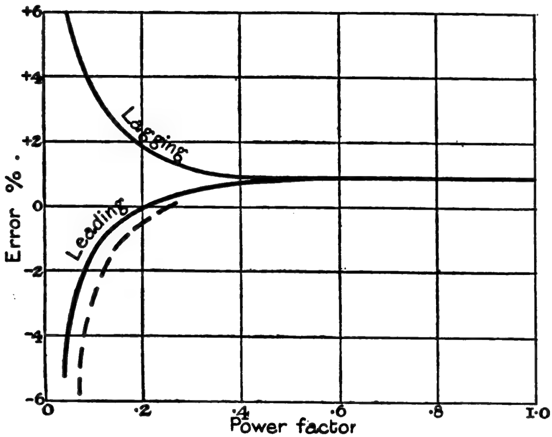


FIG. 7.—Percentage Error of Meter at different Power Factors and Constant Current.

armature of the relay being retained in its position after the shunt coil is short-circuited by the current in the series coil.

Although for lighting small houses or flats such relays would appear unnecessary, for public lighting, where reliability is of greater importance, the extra expense might be justified.

It is interesting to consider what effect might be produced on the current regulation of the lamp by the presence of the relay coils. The effect of the shunt coil will be negligible, since it will simply split the condenser current into two components in quadrature, and the relay shunt current being small, compared with the total current, will not sensibly reduce the current through the lamp. The self-induction in the series coil will reduce the total reactance of the circuit, so that by arranging for a suitable amount of self-induction in each relay, and connecting the lamp switch so as to short-circuit the relay when the lamp is not in use, the presence of the relay will improve the regulation.

For example, with a 1-ampere condenser on a 220-volt circuit, if the series coil of each relay has a reactance of 5 ohms, and if the lamp resistance is assumed to be independent of the current, the following regulation would be obtained :—

Lamp Voltage.	Current in Amperes.
0	1·000
20	1·019
40	1·030
60	1·030
80	1·022
100	1·004
120	0·980

This arrangement obviously permits of using lamps whose aggregate of voltages is more than 50 per cent. of the supply voltage, as compared with 35 per cent. when inductances are not used.

Use of Series System in Small Houses.

The series system is particularly suitable for wiring small houses or flats of 5 or 6 rooms, a class of consumer at present almost untouched by electric supply authorities and the inhabitants of which form the great bulk of the population.

In order to make electricity supply profitable in such cases it is necessary to adopt a system implying minimum costs to—

1. The supply authority.
2. The property owner.
3. The consumer.

An endeavour has been made to show that the series system fulfils these conditions in the first case by the limitation of the maximum demand, and the compensation for lagging currents, in the second case by the reduction of wiring costs, and in the third by the reduction of the initial cost of lamps and of renewals as well as the provision of a low candle-power lamp. With these advantages the system should commend itself to those supply engineers who contemplate the possibility of gaining some portion of that great body of potential consumers who are at present outside their influence.

That this system may be used with advantage for this class of consumer is apparent from the following considerations. A five-roomed house or flat would require about 8 lights giving a connected load of 140 watts and a maximum demand of 100 watts. The cost of supplying energy in such a case would be about 16s. per annum for an average consumption of 300 watt-hours per day or £1 per annum for 500 watt-hours per day, allowing £4 10s. per annum per kilowatt

of maximum demand and ¾d. per unit. It is evident that where a block of flats or houses can be supplied so as to reduce the cost of the house service to a minimum, an unlimited supply could be profitably given at from 6d. to 9d. per week. The cost of lamp renewals is of considerable amount for the long-hour consumer, being 16s. 6d. per annum for 500 watt-hours per day, assuming an average life of 1,500 hours per lamp and cost of lamps 1s. 6d. each. If the whole or even a proportion of this is borne by the consumer, this should operate so as to prevent undue waste of energy.

In conclusion, the author wishes to thank Mr. E. A. Bayles of the Helsby Works for advice and help in preparing this paper, as well as those members of the staff of Battersea Polytechnic who have also given their assistance.

APPENDIX I.

Since the actual current taken by a condenser on a circuit of given voltage and frequency is affected by the presence of harmonics, it is interesting to examine what increase of current beyond that given by a pure sine curve may be expected in the case of a mixed curve with harmonics of any given amplitude.

Let p, q, r, s, t, etc., be the ratios of the amplitudes of the 3rd, 5th, 7th, 9th, and 11th harmonics respectively to the amplitude of the fundamental; then the apparent increase of capacity due to presence of harmonics of these amplitudes can be shown to be equal to—

$$\sqrt{\frac{1 + 3^2 p^2 + 5^2 q^2 + 7^2 r^2 + 9^2 s^2 + 11^2 t^2 +, \text{etc.}}{1 + p^2 + q^2 + r^2 + s^2 + t^2 +, \text{etc.}}}$$

It will be found that for modern generators the apparent increase of capacity is not more than 5 per cent., and as it will always be an increase it can be readily allowed for.

APPENDIX II.

Effect on Lamps in Series with Condensers when Sparking occurs in the Current.

An interesting over-running effect is sometimes produced when sparking occurs at switches or loose contacts in a condenser circuit. The current through the lamp is in certain cases increased, but in other cases it appears impossible to produce any such increase of current.

The phenomenon appears to be the result of the production of an oscillatory discharge which is of a frequency higher than the normal frequency of the circuit. As a result the reactance of the condenser

is lowered and the current increased. The increased current is only maintained for a fraction of a second and cannot be measured satisfactorily on an ammeter although the temperature of the filament is obviously higher.

Whether such over-running in temperature can be produced in a given case appears to be determined by the ordinary criterion for the production of an oscillatory discharge, viz., that L is greater than $\frac{K R^2}{4}$.

In practice L is given by the self-induction of the low-tension winding of the transformer, which depends to a certain extent on the frequency of the oscillatory discharge.

If a variable resistance is included in series with the lamp and condenser and this resistance is increased until the over-running effect disappears, the calculated value of L, viz., $\frac{K R^2}{4}$, is always considerably less than the self-induction of the transformer winding at the frequency of the supply circuit, and probably corresponds to that at the higher frequency of the oscillatory discharge. If the lamp is supplied directly from an alternator without a transformer and an ironless inductance put in series with the lamp and condenser the correspondence between the actual self-induction and that calculated from $\frac{K R^2}{4}$ is fairly close.

With lamps and condensers in actual use this effect is hardly ever produced by sparking at switches, but it is liable to occur if there is a loose contact in the lamp-holder.

Discussion.

Mr. W. Perren Maycock: Having made some experiments with the condensers, I start with the assumption that their use is a practical proposition in certain cases, and I propose to show methods of controlling the lamps. It may be mentioned, by the way, that one of the incidental advantages of the condenser system is that the spark-wear at switch contacts is almost negligible. Also, if two condensers be used, bell and alarm circuits wired in the ordinary manner might be connected between them. The adaptability of what might be called the long-series connection in small houses, flats, etc., depends upon the following points: (1) The strict observance of the rule that the light in any given room should never be left on when there is no one there, even if the room be vacated for 5 minutes only. (2) The provision of means for reducing the light in rooms (such as living rooms) where a good light is sometimes, but not always, required. (3) The use of what I call restricted lighting. In a bedroom, for example, it is convenient to get light at two points; and the restriction consists in preventing both lights being used at the same time. These three necessities can only be fully secured by employing up-to-date methods of switching, and Mr. Maycock.

Mr. Maycoc . with your permission I will show you on the screen some of the various arrangements available. All the switches used—it should be noted—are of the tumbler pattern. (*Here were exhibited lantern slides showing the adaptability of various switch controls.*) I would particularly direct the attention of all concerned with electric lighting to the advantages of these controls, which are a few of many that have been primarily designed for use on ordinary circuits. The art of switching is only slightly less important than the art of illumination. Both arts are more or less ignored by the people who could and should understand them; and are as a rule left to be interpreted by people who only half grasp their possibilities.

Mr. Rawlings. Mr. W. R. Rawlings: The author has brought to our notice some very interesting facts in connection with the working of condensers in series with metal filament lamps. There is, however, I think, something still wanting in the paper, and that is some description of the apparatus itself and also of its size. It should be remembered that the size of the condenser has one of the most important bearings upon its applications for domestic purposes. We are told in the paper that a small condenser measures 2½ in. by 2½ in. by 6 in., with a capacity of 6 microfarads. That I think is too bulky for ordinary purposes when applied for single lamps such as the author suggests. Many will doubtless remember in the earlier days small transformers were introduced which had somewhat the appearance of half a German sausage hung upon the lamp-holder. By reason of its awkward appearance it never became popular. I venture to suggest that the size of the apparatus, which is described by the author, will also check its use. Again, the application of the condenser for incandescent lighting has received its death-blow by the improvements in metal filament lamps. This, however, I have felt as much as any one, for I have devoted a considerable amount of time and money on experiments in the development of the condenser for this particular application. I may say that the condenser which I use is very much smaller than that described by the author. For instance, the author's condenser contains 7·5 cub. in. or thereabouts. The condenser which I use for the same capacity contains only 1·4 cub. in. I have samples with me, and I will show you how I have applied them to domestic apparatus. The author gives an estimate for the wiring of a house to justify the use of the condenser as a saving in the wiring. I do not think he has given us a typical case. In one case he suggests the short-circuiting of the series system by switch lamp-holders, which is not to be commended, because the switch is difficult to reach. In the other case, the switch is apparently fixed at the door, and therefore it is not, I suggest, a fair comparison. If he will short circuit his lamps by a switch at the door, I think he will find that the figures he quotes will be materially modified. Then I do hope that before the paper is placed on record he will remove from it the suggestion that an estimate is based upon a system of wiring which is prohibited by this Institution. I should like to call attention to what I consider

Mr. Rawlings.

a better application for the condenser, namely, for the purpose of dimming the light. I have brought out a dimming switch which has six or seven contacts in it, and is self-contained with the condenser. It is practically the same size as the ordinary tumbler switch and block. As an example of how the dimming switch may be applied, with a lamp taking 58 watts, in the full-on position there is no condenser in circuit; the second contact will reduce to 32 watts, and the next 22, 15, 10, 5, 2, and finally off. In each of those stages there is an incandescence on the filament varying in proportion to the watts, and even on the last contact there is a perceptible incandescence. It is not a disfigurement to the fitting. I assure you that in practice it is scarcely noticeable. I have a sample here which I will show you afterwards.

There is one other thing I desire to say. I threshed this question out a long time ago, and in dealing with series lamps I realised that the amperage of the lamps was all-important. For that purpose I devised a holder which would necessitate the right amperage lamp being installed upon each individual system. For instance, one holder would be a No. 2, and another, say, a No. 3. If, then, the series system was a No. 3, all that was wanted was a No. 3 lamp giving the candle-power desired, whether it be 1 c.p. or 50 c.p. I have abandoned all idea of working in series, and so I give this away for what it is worth. I have, however, not abandoned the idea of working the dimming arrangement, because I believe that will be the best use to which the condenser can be put in connection with metal filament lamps.

Mr. Bayles.

Mr. E. A. Bayles: Representing the manufacturers of the condensers on the table, I should like to say that those which are intended for use on a circuit of 250 volts alternating have been subjected to a strain of 1,000 volts alternating. In a system of this or any similar kind it is essential that every portion of the apparatus should be absolutely reliable, and I emphasise this point because the size of these condensers has been brought before the notice of the meeting. While I admit that they can easily be made of smaller dimensions and perhaps work satisfactorily at the voltage I have mentioned, yet I would not recommend the use of a condenser on a 250-volt circuit unless it was capable of withstanding a strain of 1,000 volts alternating.

Mr. Mordey.

Mr. W. M. Mordey: It is interesting to find that condensers for power purposes are receiving practical attention. Mr. Rawlings' speech shows there are two sides to this question. I had hoped in the discussion to-night to have heard something more on the principles of the proposed system rather than on the details, although I realise that the success of any system of this sort must depend largely on the details. The author's paper brings before us for the first time a new view of the use of condensers in practical work. I look upon it as an interesting departure, and I cannot help thinking that in time it will become important. It shows us that electrostatic condensers have now arrived at such a stage of development that they may be regarded as

Mr. Mordey. practical engineering tools, ranking with transformers in their practical qualities. This position has not been generally recognised by electrical engineers hitherto. It is three years since I read a short paper on "Some Tests and Uses of Condensers" * to which the author referred, and I am pleased to find that his tests practically confirm the results I then gave. Although too much may be made of no-load or magnetising losses or their equivalent, there is an important difference that is well brought out by the results given in the paper, between condensers and transformers. A great difficulty, as we all know, in transformers, is that whilst it is easy enough to make large ones with a small no-load loss, it is not practicable to do that with small ones. With condensers, on the other hand, the no-load losses are very small, even in the smallest sizes. Taking from Fig. 3 the 8-microfarad condenser, for a load of 50 watts, we see from a previous figure that the total loss is less than half a watt. That is very satisfactory, especially in an apparatus with so large a margin of safety. The proportional loss is the same for all sizes—a large condenser being simply a collection of small ones. Not only is the no-load loss small, but there is no other loss, as the C^2R is negligible. The qualities illustrated which seem especially interesting and important, are the self-regulating property for series or parallel working and preventing excessive current due to a sudden rush of current when switching lamps on, or to other causes.

Messrs. Pyke and Barnett. Messrs. L. PYKE and H. T. BARNETT (*communicated*): The description of the author's experiments reminds us that some twenty-five years ago we were perhaps the first to use condensers in series with sources of light in order to enable distribution of current to be effected with ease where otherwise there would have been difficulty. The sources of light we used in those days were vacuum tubes, and the condensers were connected each in series with a tube or series of tubes in order that a number of such sets might be worked in parallel from one of our powerful spark coils. These condensers had foil surfaces only a few inches square, so that their size was not such as to tempt us to make exact measurements of their characteristics, especially as it was obvious that in practice the losses involved by their use were negligible; therefore we employed them a good deal in the demonstrations of vacuum-tube lighting in which at that time we were interested. In reference to condensers of greater size, however, our work of those days in developing the condenser for spark suppression on coil breaks may be of interest now, indeed of far more interest now than then, if there is a scope in practical utility for such apparatus in connection with metal filament lamps on alternating-current circuits. For our spark coils we needed compact condensers of great capacity, good insulation, and great dielectric strength, capable of remaining unchanged in any climate; and not being at all satisfied with paraffin wax condensers on these points we did much tedious and expensive experimenting, as a result of which we were enabled to turn out quickly and cheaply a condenser insulated

* *Journal of the Institution of Electrical Engineers*, vol. 43, p. 618, 1909.

Messrs. Pyke and Barnett.

with ozokerit wax: in form a hard solid block and containing no vacua or watery or weak places formed by contraction of liquid wax within an already cooled outer crust. Ozokerit is a hard black mineral wax (possibly also sold under other names), and the quality that we used remains solid even at equatorial temperatures, and may be worked when cold almost like ebonite, especially if impregnating some absorbent. Like paraffin wax, it is hygroscopic, and contains water when purchased; but it may safely be heated to a temperature that will drive the water off, and, once got rid of, water is not re-absorbed at all readily. The manufacture of the condensers was covered at the time by Patent No. 1024 of 1888, but of course this has long since expired and the method is now open to all to use. The only essentials to observe are these: (1) That the water in the wax shall all be boiled off; (2) that cooling shall proceed from one direction only, in order that there may be a steady flow of melted wax through the material to make up for the contraction of that part already in process of hardening; and (3) that the cooling shall proceed at such a slow rate as to render this movement through the paper of the melted wax easily possible. One of these condensers, made at that time and measuring $6\frac{1}{2}$ in. × $7\frac{5}{8}$ in. × $\frac{3}{4}$ in., and which has been shifted from one damp cupboard to another during the past twenty-four years, has recently been re-tested by the Silvertown Company. Its capacity is found to be 2·8 microfarads, and its insulation resistance after 1 minute's electrification amounts to 0·2 megohms per microfarad, it withstanding a dielectric stress of 450 volts. Of course, in considering the capacity the thickness between foils must be taken into account, and we used no less than three layers of strong music demy between foil, as it is necessary for spark-coil work that the dielectric strength should be great, the low resistance found being due to re-absorption of moisture by the ozokerit during its long immersion in damp air. Seeing how great a loss is produced by the small hygroscopic characteristic of the wax at the end of a considerable period of time, it would appear to us to be advisable in all cases where the loss is an all-the-year-round one, as in electric lighting plant comprising condensers permanently connected in circuit, that the condensers should be hermetically sealed. We never tried tinned paper instead of the usual foil; of course tin was a different price at that time, therefore in view of present conditions we do not fail to estimate very highly indeed the Helsby method of making condensers from the cheaper article. We hope this short note may be useful in still further cheapening and perhaps in also rendering smaller and more serviceable condensers for use in the system the author is pioneering.

Mr. Campbell

Mr. ALBERT CAMPBELL (*communicated*): There are many matters of great practical interest in the author's paper. The great improvement in paraffin paper condensers due to the new process is very welcome, and may point the way to further advance. The power factor is of course a crucial point, and it is on this that I wish to make a few remarks. The author states that the power factor is by no means constant for different voltages, and, as Fig. 2 shows, the power factor

Mr. Campbell.

may increase by 200 per cent. when the voltage is reduced from 240 down to 80 volts. Now it is extremely difficult to accept this result as correct, unless the condenser is of an entirely abnormal type. It appears to contradict the results of so many previous experimenters, who concur in finding these power factors constant with varying voltages (for constant frequency and sine wave-form). For example, B. Monasch has shown* that over a range of 2,000 to 5,000 volts the power factors of condensers of glass, ebonite, impregnated paper, indiarubber, and other materials, remain extremely constant. To take a case more similar to that in question, the following table gives some results which I have obtained with an ordinary small 2-microfarad telephone condenser of Mansbridge type. The tests were made by the Carey Foster method, which is without doubt one of the most accurate ways

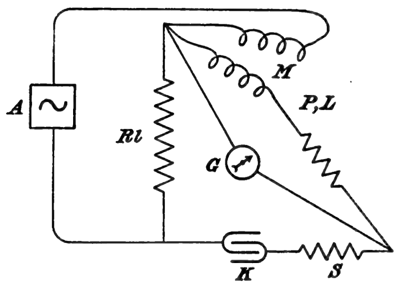


FIG. A.

of determining condenser losses. The frequency was 100 ∿ per second, and the detecting instrument a vibration galvanometer, so that the results hold for a pure sine-wave voltage.

Volts.	Power Factor.
5	0·00834
30	0·00841
100	0·00839

The power factor here is seen to remain practically constant. With a little more care in keeping the temperature and frequency constant, it is probable that the three values would have shown agreement to the last figure. Similar tests on a Fuller telephone condenser with real tinfoil showed a power factor of 0·0035. It appears probable that the variations shown in the author's tests were really only the errors of the wattmeter method, which requires to be used with the utmost caution for such low power factors. As this use of the Cary Foster method is not sufficiently well known, I add a short description :—

* *Electrician*, vol. 59, p. 416, 1907.

Let— Mr. Campbell.

A be a source of alternating current,
G a vibration galvanometer or telephone,
M a mutual inductance,
K the condenser under test,
R, P, l and L the respective resistances and self-inductances of the arms as shown,
S an added resistance,
s the effective internal resistance of the condenser,
$\omega = 2\pi \times$ frequency.

Then if a balance is obtained by adjusting S and M or S and P we have

$$K \doteq M/PR \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where K and M are in microfarads and microhenries, and—

$$S + s = R\frac{L-M}{M} + \frac{l}{M}P \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

From equation (2) we immediately obtain s; the power factor may be taken as $\omega K s$. Although l is usually very small, the second term in (2) is not necessarily negligible.

Mr. F. W. HEWITT (*communicated*): In discussing the use of the series system in small houses the author gives, for a typical case, the cost of energy as £1 per annum and of lamp renewals as 16s. 6d. As this may give a wrong impression of the relative cost of energy and lamps, I wish to correct his figures for the cost of lamp renewals. The author assumes a house requiring eight lights aggregating 140 watts; that is, lamps averaging 17½ watts each. For the consumption of 500 watt-hours per day, this represents 28½ lamp-hours daily, or 10,400 lamp-hours per annum. The average life of 1,500 hours assumed by the author therefore means seven lamp renewals per annum and a cost, at 1s. 6d. per lamp, of 10s. 6d., instead of 16s. 6d. In practice the ratio of the cost of energy to cost of lamps might work out at less than this. Mr. Hewitt.

I have noticed a peculiar flickering of the light of a lamp connected in series with a condenser on a public supply circuit, which flickering only occurs late at night, and may possibly be due to the type of plant used for the all-night load. This flickering was not noticeable on lamps used without the condenser.

Mr. A. W. ASHTON (*in reply*): With regard to Mr. Maycock's suggestion that with the series system it would be very necessary to switch off the lamp in any given room before vacating it, this appears to me to be important only in so far as the lamp left on restricts the use of other lamps on the same condenser. The danger of such a lamp failing while alight, and so putting out all the lamps in the same series connection, appears very remote. Experience has shown that lamps very seldom fail after being alight for any considerable time, but that Mr. Ashton

Mr. Ashton. failures occur either when the lamp is cold or when it is first switched on. Mr. Maycock's diagrams of switch circuits are very interesting, and there appears to be room for considerable improvement in the methods of switching at present generally adopted. The method of obtaining "dim" lighting by putting parallel lamps in series, or with a condenser by putting series lamps in parallel, is very inefficient. The "dim" lamps give each about one-sixteenth of their normal candle-power, and take about one-third of their normal wattage, *i.e.*, the watts per candle-power will be about five times the normal. Now with a condenser it is possible to get a "dim" light by using a 5-watt lamp run at a little less than its normal efficiency, provided the rated current of the small lamp is the same as the lamp and condenser with which it is in series.

Mr. Rawlings raises an important point with regard to the use of slip socket fittings as the basis of the comparative estimates of wiring costs. It does not appear clear that slip sockets are intended to be prohibited by the Institution Wiring Rules, provided continuity is obtained by some system of earthing grips. In any case I should say that 99 per cent. of ordinary dwelling houses using electric lighting are wired with slip sockets without any special method of obtaining continuity, and that wiring is being carried out on this system by a number of large supply authorities. With regard to Mr. Rawlings' suggestion that I should cut out all mention of this system from the paper, I shall be glad to do so if he can prevail on the members of the Electrical Contractors' Association to pull the slip socket out of the houses they have wired. With regard to Mr. Rawlings' criticism of the size of the condensers for a given capacity, this depends largely on the factor of safety considered necessary. The condensers in use at present are strained at 1,000 volts for use on circuits up to 250 volts; by reducing the straining voltage to 500 it would be possible to reduce the dimensions of the condensers to about one-quarter of their present size. It is not considered advisable to reduce the factor of safety, because it is realised that in order to extend the use of condensers an absolutely reliable article must be offered. Another possible method of reducing the dimensions is by using a material having a higher dielectric constant than paraffin paper. Unfortunately those substances which have a high dielectric constant are characterised either by large dielectric losses or by want of permanence in their mechanical and electrical properties, and are thus quite unsuitable for general use on alternating-current circuits. Mr. Rawlings is discreetly silent as to the method adopted to obtain the small volume per microfarad in the condensers he has exhibited, nor does he give any particulars of the dielectric strength or losses of the condensers. I do not think the reduction of the dimensions is so necessary as he assumes, as the condenser can generally be put in such a position that its dimensions are relatively unimportant.

The particulars given by Messrs. Pyke and Barnett concerning the use of ozokerit as a dielectric are very interesting; exhaustive tests have, however, been made by the Helsby works, not only with ozokerit

but with practically all waxes commercially available, and these experiments tend to show that paraffin wax, when properly treated, is the most satisfactory dielectric for condensers of this type. Mr. Ashton.

With regard to Mr. Campbell's communicated remarks on the abnormal variation of power factor with voltage shown in Fig. 2, I have made further tests on the same condenser, and have not been able to obtain consistent results at voltages below about 150. The question is complicated by the fact that if the current resistance is varied in the electrometer test, the curve of watts loss plotted against current resistance is not a straight line, so that the result obtained by extrapolating for zero current resistance becomes rather indefinite. This is particularly noticeable at the lower voltages, in which the loss becomes so small. To obviate this difficulty, I have made further tests at low voltages by using a number of exactly similar condensers in series. The average of a large number of results obtained in this way is 0·38 per cent. for 125 volts 50 ∿, and 0·40 per cent. for 250 volts 50 ∿. I have also confirmed this result by Wien's bridge method using a vibration galvanometer. The abnormal result shown in Fig. 2 may be due to extra losses caused by the resistance of the connecting strips. A certain amount of resistance may have been introduced in series with the condenser at the lower voltages, due to imperfect connections which would give disconnections at low but not at higher voltages. The Carey Foster method described by Mr. Campbell would appear to be a very satisfactory method of determining the losses in condensers of the type described, as with Wien's method an air condenser must be used which for maximum sensibility should be almost equal in capacity to the condenser tested. This makes it rather difficult to use this method for measuring the losses in condensers of about 20 microfarads.

In reply to Mr. Hewitt's communicated remarks, the cost of lamp renewals has been calculated on the assumption of 5 hours use per day of the maximum demand of 100 watts, thus giving 40 lamp-hours per day instead of 28, as calculated on the assumptions made by Mr. Hewitt. With regard to the flickering observed on the lamps at night, this is probably due to rather violent cyclic variations of the prime movers.

SPECIAL RESOLUTION

Passed 9th May, 1912; *confirmed 30th May*, 1912

At an Extraordinary General Meeting of the Members and Associate Members of The Institution of Electrical Engineers, duly convened, and held in the Lecture Theatre of the Institution, Victoria Embankment, London, W.C., on Thursday, the 9th day of May, 1912, the subjoined resolution was duly passed; and at a subsequent Extraordinary General Meeting of the Members and Associate Members of the said Institution, also duly convened, and held at the same place on Thursday, the 30th day of May, 1912, the said resolution was duly confirmed as a special resolution:—

> "That the Articles of Association contained in the printed document submitted to the meeting and for the purpose of identification subscribed by the Chairman thereof be and the same are hereby approved, and that such Articles of Association be and they are hereby adopted as the Articles of Association of the Institution, to come into operation as and from the 1st day of July, 1912, to the exclusion of and in substitution for all the existing Articles thereof."

TARIFFS FOR ELECTRICAL ENERGY, WITH PARTICULAR REFERENCE TO DOMESTIC TARIFFS.*

By W. W. LACKIE, Member.

(*Discussion before the* NEWCASTLE LOCAL SECTION, *22nd April*, 1912.)

Mr. A. S. BLACKMAN: I note that on page 156 the author refers to the responsibility of municipalities in furthering the general movement towards public health by nursing their electrical undertakings, by encouraging the use of electrical energy for all domestic purposes, and am struck by the fact, that with this aspect of the case in mind, he has framed tariffs with a basal price of 1d. per unit, which is perhaps in consequence of the competition in Glasgow being of a less strenuous character than has to be met in some other towns. In Sunderland, for instance, we have to contend with gas at 1s. 10d. per 1,000 cub. ft. for ordinary lighting purposes through ordinary meters, and in addition to this, the provision of high-pressure gas lamps and ordinary gas mantle maintenance at prices which cannot possibly pay the suppliers, with the result that we were unable to make any headway with the use of electricity for general domestic purposes until the price for heating, cooking, etc., was reduced to ½d. per unit. In bringing this about, we based our tariff on the one Mr. Long introduced at Norwich, viz., an annual charge in the form of a percentage upon the rateable value, but differing from Norwich, and I believe from all other towns that have adopted the Norwich system, by reason of our having made the percentage upon the rateable value a sliding scale, the percentage increasing with the rateable value, the actual scale adopted being as follows: For houses of not less than £15, nor more than £30 assessment, 10 per cent. per annum on net rateable value; above £30 and not exceeding £40, 11 per cent.; above £40 and not exceeding £50, 12 per cent.; above £50 and not exceeding £60, 13 per cent.; above £60 and not exceeding £70, 14 per cent.; above £70, 15 per cent. One-third of the fixed rental to become payable at the end of the quarters ending in December and March respectively, and one-sixth of such rental to become payable at the end of the quarters Mr. Blackman.

* See p. 147.

Mr. Blackman. ending in June and September respectively. Periods of less than one quarter to be paid for *pro rata*.

The only rate previously in force for private house lighting was a flat charge of 3·6d. per unit, and this remains available at the consumer's option, but we find that the rateable value tariff, or as we call it, the "domestic rate," generally results in a reduced cost of lighting where houses are electrically lighted throughout, and it consequently follows that all units used for other purposes are obtained at the flat rate of ½d. per unit. The unit price was originally ¾d., but after nine months' experience this was reduced to the present figure, and this domestic rate, which is, of course, only available for private houses, has been a great success, and has fully achieved its object. In addition, we supply electricity for cooking and heating purposes to any premises which use electric light at the flat rate of ¾d. per unit. I consider that all sets of tariffs should include a special rate for such premises as public-houses, hotels, and shops, which are open for seven days per week. Consumers of this class can under any ordinary demand indicator system obtain electricity at a low rate, and are often lost to the electricity supply because they fail to understand the system of charging, and it is very easy to arrive at the load factor of these consumers and declare a special rate to meet their circumstances. In Sunderland we some twelve months ago declared a special rate of 1⅞d. per unit for this class of work, and have since coupled up a great many consumers by reason of it, some of them being new installations, and others installations that we had previously lost to the Gas Company, under the old system of charging. In framing tariffs it is often useful to take a hint from other businesses; probably the drapery business is conducted as shrewdly as any, and every one is familiar with the draper's 11¾d. In framing new tariffs I have followed the same line, and the Sunderland tariffs contain such prices as 1⅞d. and 2⅞d. per unit. The reduction in revenue as between these figures and 2d. and 3d. respectively is negligible when the assistance of the lower rates to the canvassers is taken into account.

Mr. Lunn. Mr. J. R. P. LUNN: There is no doubt that some improved system of charging is very much needed at the present time, but I do not feel satisfied that the principle on which the Norwich system and the system adopted by the author in Glasgow are based, is altogether sound. In these systems it is taken for granted that electricity can be supplied for cooking and heating by means of any kind of apparatus the consumer chooses to use, at from ½d. to 1d. per unit according to the unit charge adopted. The charge for electricity for cooking and heating appears to be fixed according to the price that the consumer will pay for a supply for this purpose without any regard to the cost of providing such a supply. I am sorry that the author has not gone more into the question of what load factor and diversity factor we may expect to get with cooking apparatus if electric cooking is taken up seriously and large ovens, etc., are generally used. A system of charging for cooking and heating ought, I think, to take into account in some way

the load and diversity factors of the cooking demand, and neither the Glasgow system nor the Norwich system do this. For instance, if all the domestic lighting consumers whose average lighting demand is less than a quarter of a kilowatt were to go in for general cooking by electricity, they would each require an oven taking 3 or 4 k.w., and if all these ovens were in use at the same time a large increase in the capacity of the mains and possibly of the generating plant would be required. We do not know to what extent these ovens would be in use at the same time or what proportion of them would be on at the same time as the lighting peak load, but I am given to understand by gas engineers that the gas cookers all appear to come on at the same time. Another point in this connection is that the most efficient kind of oven appears to be one that uses a comparatively large current and heats up very quickly, as this reduces the radiation losses. Also a large radiator which will heat up a room quickly and can then be partly turned off is more convenient than one which is kept going steadily all the time. Unless the increase in the diversity factor due to the shorter use of the heavier current will eliminate the possibility of the peak load being seriously increased the system of charging should impose some check on the adoption of heating and cooking apparatus of the above description. I do not quite understand how the author gets the amount of electricity used for lighting from a recording ammeter unless he takes it that all electricity used during lighting hours is used for lighting. Then as to the method of using a recording ammeter for arriving at the lighting demand in the larger houses it seems very likely that, if the consumer understood the system of charging, the demand when the recording ammeter was put in might be very different from the demand which would be made later on. Mr. Lunn.

Mr. W. F. T. PINKNEY: Referring to the rateable value tariff which is in use in this district the standard charge is 12½ per cent. on the rateable value of the house and ¾d. per unit for current supplied. It has not been long in use, but looks as if it would be a very good system of charging. Under this system the average use for the maximum demand is considerably more than the 2·7 hours given in Table VII. for domestic use, and is more like 4 hours, but I have not figures to verify this. It seems to me that Glasgow must have a very large number of recording ammeters, and I do not know if it is the author's practice to put recording ammeters into a very large number of his consumers' premises as well as unit meters in order to arrive at his figures. If so it will run up the meter costs very much. Mr. Pinkney.

Mr. SYDNEY WINDLE: Upon page 150 the author states that where gas can be obtained for 2s. per 1,000 cub. ft. or more, there is no necessity to supply electricity for lighting at less than 3d. per unit. I think the figure for electricity is too high, but perhaps the author will explain how he has arrived at this conclusion. The most important lesson suggested by the paper is the necessity for a good diversity factor, which can only be obtained where cheap electricity is available for all classes of consumers and graded rates are provided to suit the load Mr. Windle.

Mr. Windle.

factors of the various classes of supply. In Sunderland we are endeavouring to meet this condition with the present rates, and the success of the "domestic" tariff is largely due to the low unit charge which enables this class of consumer, after paying a small fixed rental, to use lighting, radiators, flat-irons, cookers, and other domestic appliances at ½d. per unit. The rate is easily understood and can be handled to advantage by the canvasser, who is able to show the householder that additional units are not going to run up a big bill, and that the addition of, say, 200 units will only cost 8s. 4d. The author's charge of 1d. a unit is too high for successful business, as consumers will find it too costly to make constant use of their cookers or comfortably to warm their rooms with radiators. It is the varied use of consuming devices that makes the house supply a profitable one, and results in a high diversity factor, which in turn reacts favourably upon the generating plant, enabling us to give cheap supplies.

Professor Stroud.

Professor H. STROUD: Modern electric heaters are, in my opinion, in every way superior to gas fires. An important point is simplicity in the matter of charging. Thus I am in favour of a fixed annual charge and a small price per unit. I am much against the maximum demand system because it discourages gradual extensions. Before inviting the general adoption of electric heating and cooking, the question of the size of their mains was, no doubt, very fully considered by the power companies concerned.

Mr. Proctor.

Mr. C. F. PROCTOR: It seems to me that cooking by electricity is a line we do not want to encourage, because the load comes on all at once. It is very easy to recognise this when walking past some of the large works at dinner-time; thousands of men are going home to dinner and the meals have all to be cooked at the same time. As regards heating I should like to know what is the cost of heating a room, say, 20 ft. × 18 ft. I understand the cost of heating by coal is 3d. per day; by gas it is 8d. to 1s. per day, and I have been told that I could not possibly do it by electricity under 1s. 6d. per day with electric energy at 1d. per unit. Now, however, that we hear of energy being supplied at ½d. per unit, I think electrical heating would just about be able to compete. As far as I am able to gather, electric heating is very slow. It takes about 2½ hours with the kind of heating apparatus that is mainly used.

Mr. Brown.

Mr. C. S. VESEY BROWN: The first thing to consider in a tariff is simplicity. Of course the importance of adequate return on capital outlay is to be considered. When Mr. Wright evolved the demand indicator system, it was entirely a question of expediency in order to produce a revenue sufficient to cover working charges and interest on capital, and at the same time to keep off the short-hour consumers who demanded first supply at such a rate as would not leave a margin of profit. Owing to the manner in which the capital is employed in electrical supply, it is difficult to fix any flat rate in the same way as the gas industry is able to supply its consumers, and it will take a long time and greater application of domestic uses before the long and short-hour consumers can be lumped together to produce a flat rate satis-

factory to both parties. With regard to the author's remarks on the assumed advantages which a private company has over a municipal ownership, I take some exception to this statement. For instance, a municipal authority not 100 miles from Newcastle do not recognise that all churches and places of public worship, public halls, etc., should be charged at the same rate as public lighting. If such an undertaking was in the hands of a private company some dissatisfied shareholder would be able to raise the question at the next general meeting, but in the case of a municipal authority there is no annual general meeting and it is very difficult to get at the municipal authority excepting through the Attorney-General. I should much like to know what the capital expenditure of a consumer is for the small houses, and it would also be interesting to know whether the small consumer who is situated some distance from the mains, say 200 yards, receives the same attention as the consumer who is on the mains. **Mr. Brown**

Mr. LACKIE (*in reply*): Mr. Blackman thinks we are charging too much in asking for 1d. per unit for all energy used in connection with cooking when he only charges ½d. per unit. I would point out, however, that if we in Glasgow got between 10 and 15 per cent. of the annual rental of the premises first, we could almost give energy away for nothing. The average account for lighting in Glasgow is only about 5 per cent. of the rental. If the rates on the maximum demand system are properly fixed, viz., a fairly high initial rate for the first hour and a low rate thereafter, the maximum demand system should meet all cases of public-houses and hotels running for long hours. **Mr. Lackie.**

Mr. Lunn referred to the peak load for heating and cooking, and fears that the existing mains will be overloaded. The diversity factor of cooking has been found to be very high, and I do not find excessive peaks. It has further to be remembered that the mains and wiring have been laid down to suit carbon filament lamps and in some cases a pressure of 100 and 110 volts. Heating and cooking also go on all the year round and at all hours of the day. Recording-ammeter records were obtained quite twelve months before the new rate was offered, and maximum demands for all classes and districts in the city were got before any heating or cooking had been installed, so that all energy used during lighting hours was really used for lighting.

Mr. Proctor referred to the large number of workmen going home for dinner at the same hour. It must be kept in mind that the plant that was used to drive the works these men have just left will be used to drive the cars carrying them to their homes and afterwards for cooking their meals. For the heating of a room for an hour or two, electricity is as economical as either gas or coal if all the considerations are taken into account.

Mr. Windle says he questions if 3d. per unit for electricity is equivalent to 2s. for gas. Here again we have numerous instances of electric light being substituted for gas at 2s. and the consumers' bills are no more than they were, and in many cases they are less.

Mr. Vesey Brown has misunderstood my reference to private com-

Mr. Lackie. panies *versus* municipal ownership. The point I wished to make was that private companies can, and do, consider each case by itself in a commercial spirit and quote rates to meet each case. A municipality is tied up and has to publish its rates and treat all consumers in similar circumstances alike. The capital cost per consumer I have given in my reply to the London discussion on the paper. I am sure that the small consumer 200 yards away receives the same treatment as the consumer on the mains.

YELLOW FLAME ARCS.

By MAURICE SOLOMON, Member.

(*Paper received 16th April, received in final form 27th April, and read before the* BIRMINGHAM LOCAL SECTION *on 24th April,* 1912.)

INTRODUCTION.

Although it is now over ten years since the first introduction of the flame arc, there has not been presented to the Institution any paper dealing with this subject. The paper by Mr. Andrews, entitled "Long Flame Arc Lamps," read before the Institution in April, 1906, scarcely dealt with the flame arc at all, as it is now understood, but describes a particular lamp in which an ordinary open type arc is drawn out into a long non-luminous flame by the use of a high voltage across the arc-gap. Nowadays, however, the flame arc is understood to mean an arc in which, by the incorporation of certain chemicals in the carbons, a long flame of high luminosity is produced. The idea of increasing the light-giving power of the arc in this way is a very old one, but modern progress starts from the investigations of Bremer on the use of fluorides in the carbons. The type of carbon worked out by Bremer is now practically no longer used in the industry, but it served to show the greatly increased efficiency that could be obtained, and in principle at least is the prototype of all modern flame carbons. Development has been rapid during the past five or ten years, and the flame carbon has not only been brought to a state of great perfection, but has also been to a large extent standardised so that the time is not perhaps inopportune for reviewing the present position of the subject. This is especially justified in view of the fact that the flame arc has produced in the field of exterior lighting and the lighting of large interiors a development as important as that produced by the tungsten lamp in the field of interior lighting. To-day it stands unchallenged as the most efficient form of artificial illuminant yet produced by man.

FLAME ARC LAMPS.

No attempt will be made in this paper to describe the construction and details of the various types of flame arc lamp now on the market, as the paper does not profess to deal with flame arc lamps, but with the flame arc itself. The author may perhaps be pardoned if he looks on the flame lamp merely as a mechanism for ensuring the regular and steady burning of flame carbons, but apart from any bias which he may have, it cannot be gainsaid that the high efficiency which has been attained

is a triumph not for the arc lamp-makers but for Bremer and the carbon manufacturers who have followed his lead. There are, however, two respects in which the flame arc lamp differs more or less radically from the open type arc lamp. The first is the more or less universal use of carbons inclined to one another at a slight angle with the arc burning across their lower ends, in the place of carbons arranged vertically one above the other, though this type of lamp is still used in some special cases. This arrangement, rendered possible by the length of the flame arc, contributes to some extent to the efficiency of the flame lamp since it exposes fully the crater of the positive carbon; that it contributes but little is shown by the fact that the efficiency of the pure carbon arc between inclined carbons is little, if any, better than that of the ordinary open arc between high-grade carbons. The figures given by Mr. Andrews, in the paper to which reference has already been made show a power consumption of approximately 0·9 watt per mean spherical candle; the open type arc between carbons of similar quality has a power consumption of about 1·1 watts per mean spherical candle. In practice, therefore, the gain by exposing the crater is counterbalanced by the loss of power in the arc showing that no great improvement would have been effected by this method of lamp construction if the low-voltage flame arc had not been developed. The second characteristic of the flame lamp is the use of the economiser: this is the inverted bowl in which the arc burns. The economiser acts as a good reflector above the arc and retards the rate of consumption of the carbons; in addition, it greatly assists the steady burning of the arc by the way in which it partly confines the flame and corrects to a certain extent irregularities in the burning of the carbons. The shape of the economiser varies in different lamps, but in all the same end is attained, that the red-hot tips of the carbons are situated in an atmosphere which has been partly robbed of its oxygen; as a result the carbons burn away more slowly, but in addition the economiser tends to make them burn away at equal rates. For if one carbon burns more slowly than the other its point will project beyond the base of the economiser into an atmosphere richer in oxygen, and its rate of burning will be accelerated; unless the natural disparity in the normal rates of burning of the two carbons is considerable, this correction is sufficient to make them burn in practice at equal rates and to keep the ends of the carbons level and the arc at the proper height. There can be no doubt that the economiser is a valuable contrivance which has helped considerably in the development of the flame arc.

Apart from these two features, the flame arc lamp does not differ materially from the open type arc lamp. In many respects indeed the flame arc presents a much simpler problem to deal with than the ordinary arc. The great length of arc which renders possible the use of magnetic control of the arc itself, the fact that slight variations of voltage are naturally of less importance when the arc length is 10 to 15 mm. instead of only 2 mm. and the fact that small changes in the length of arc are without so great an effect on the volume of light

have indeed led to the development of arc lamps of much simpler construction as, for example, the "Beck" and "Butt" lamps, in which the feeding of the carbons is done simply by gravity. Another noticeable feature in the history of the flame lamp during recent years has been the perfecting of the magazine lamp, which is the natural outcome of the desire to combine the advantages of the flame arc with the benefits of long burning hours and relatively cheap carbons.

Flame Arc Carbons.

The flame carbons originally patented by Bremer were solid carbons made from a homogeneous mixture of carbon and colouring material. This type of carbon has not, however, proved satisfactory in practice, mainly on account of the difficulty of preventing the formation of slag on the tip of the carbon during burning. The real advance due to Bremer is therefore the demonstration of the gain in efficiency to be obtained by incorporating fluorides in the carbon, and the discovery of the most suitable percentages of fluoride to use. It has indeed been found that the percentages proposed by Bremer in his patents are somewhat too high; but, nevertheless, his work indicated definitely the lines on which future progress has been made. It was natural that the carbon manufacturers should endeavour to make use of the cored carbon, and should try to obtain the Bremer effects by incorporating the flame-producing material in the core only; these efforts met with complete success and, after experience had shown the best ratio between the diameters of the core and the carbon and the best composition for the core, the cored carbon took the place which it still holds as the standard flame carbon.

The standard flame carbon in use to-day is therefore simply a cored carbon having a core of special composition. The outer shell is pure carbon made from the same material as the carbons used in open or enclosed type arc lamps. This material is a mixture of finely ground gas retort carbon and lampblack, or soot; these materials are mixed with tar as a binding agent, pressed into tubes under great pressure, and baked at a high temperature. As is well known, most manufacturers make open type carbons of more than one grade; the high-grade carbons are made from a base mixture containing 70 to 80 per cent. of soot, and low-grade carbons (the standard in use in this country) from base mixtures containing 30 to 50 per cent. of soot. The advantages of the high-grade carbons are increased efficiency of the light, steadier burning, and the production of less residue during burning; the disadvantages are higher cost and shorter burning hours. In making flame carbons the same effects are produced according to the base mixture used for the shell, but as the cost of the base mixture plays only a slight part in the final cost of the carbon, there is less inducement to sacrifice the advantages of the high-grade mixture for the sake of a very slight gain in burning hours and in cheapness. It will be found, therefore, that nearly all manufacturers make the shells of their flame carbons from a high-grade "soot"

mixture. In some cases low-grade mixtures are used, but this is, so far as the author knows, due to pressure from the arc lamp-makers who have preferred to sacrifice efficiency to a trifling gain in cost of maintenance.

We see, therefore, that the shell of the flame carbon does not present any special features. The differences lie in the composition of the core and the design of the carbon. By the design of the carbon is meant the ratio between the diameters of the carbon and the core, and the diameter of the carbon intended for a certain current and other similar characteristics. The core of a flame carbon is much larger than the core of an open type carbon of the same diameter, and the diameter of a flame carbon for a certain current is much smaller than that of the corresponding open type carbon. This is brought out more clearly by the figures in Table I. which represents average practice.

The figures in Table I. for the diameters of the cores are correct for the carbons made by my own company, but will be found to vary slightly in carbons of different makes. The table brings out a point of the first importance, namely, that the diameter of the core in a carbon used as a positive in a direct-current lamp is considerably larger than that of a carbon of the same size used as a negative: we may at once divide the standard flame carbons into two classes, based on this difference, namely :—

Large-core flame carbons

and—

Small-core flame carbons.

The names are not very happy, as in both cases the cores are large compared with ordinary carbons, but they are the best that the author can suggest. One is tempted to call the large-core carbons "positives," and the small-core "negatives," in accordance with the most common practice in direct-current lamps, and at one time the author used these names. Unfortunately, however, as will be seen later, this practice is not universal, and confusion arises when one speaks of a "negative" carbon being used as the "positive" in some particular lamp, or when one speaks of two "negative" carbons being used in an alternating-current lamp.

The diameter of the core in the large-core carbons is, as will be seen from the table, one-half the diameter of the carbon : its area is, therefore, one-quarter of the total area. In the small-core carbon the core diameter is one-third and the area of the core one-ninth. The importance of these dimensions will be dealt with presently when discussing the composition of the core. Before considering this question, it will be well to refer to another point in connection with the design of the carbons, namely, the use of such small diameters. This has been necessitated by a number of circumstances, but, without entering into too much detail, one may say broadly that the size of the core is determined by the current and the size of the carbon by the necessity for obtaining equal rates of burning for the core and the shell. The diameter of the core should be such that the area of the arc

TABLE I.

Diameter of Carbons and Cores used in Direct-current Lamps.

Current.	Open Type Lamps.				Flame Lamps.			
	Positive.		Negative.		Positive.		Negative.	
	Carbon.	Core.	Carbon.	Core.	Carbon.	Core.	Carbon.	Core.
6 amperes	14 mm.	3·0 mm.	9 mm.	Solid	8 mm.	4·0 mm.	7 mm.	2·3 mm.
8 ,, ...	16 ,,	3·5 ,,	10 ,,	Solid	9 ,,	4·5 ,,	8 ,,	2·7 ,,
10 ,, ...	18 ,,	4·0 ,,	12 ,,	Solid	10 ,,	5·0 ,,	9 ,,	3·0 ,,
12 ,, ...	20 ,,	4·5 ,,	13 ,,	Solid	11 ,,	5·5 ,,	10 ,,	3·3 ,,

TABLE II.

Type of Carbons used.	Most General.		Fairly General.		Occasional.		Recommended.	
	Positive.	Negative.	Positive.	Negative.	Positive.	Negative.	Positive.	Negative.
Direct-current, metal-cored ...	L.C.F.	S.C.O.	S.C.F.	S.C.F.	L.C.F.	S.C.F.	L.C.F.	S.C.O.
Direct-current, coppered ...	S.C.F.	S.C.F.	L.C.F.	S.C.O.	L.C.F.	S.C.F.	L.C.F.	S.C.O.
Direct-current, plain	S.C.F.	S.C.F.	L.C.F.	S.C.O.	L.C.F.	S.C.F.	L.C.F.	S.C.O.
Alternating-current, M.C., Cop., or Plain ...	S.C.F.	S.C.F.	—	—	—	—	S.C.F.	S.C.F.

crater is equal to, or slightly larger than, the area of the core; if the crater is much larger there will be a loss of efficiency; if smaller, the arc is likely to wander and to be unsteady. These considerations produce two undesirable results, first that the rate of burning of the carbons is rapid, and second, that their resistance per unit-length is high. The high lineal resistance is increased by the large diameter of the core, which is itself of very low conductivity. The rapid rate of burning of the carbons is corrected to a certain extent by the economiser; thus calculating on the basis of area we should expect the standard flame carbon to burn length for length between three and four times as rapidly as open type carbons, whereas actually they only burn between two and three times as rapidly. This difference is, however, sufficient to have made it necessary to use much longer carbons in order to obtain reasonable burning hours with one trim, and the majority of single-carbon flame lamps are constructed for carbons from 16 in. to 30 in. long. This accentuates the second disadvantage of the high lineal resistance, for if a lamp is constructed for 24-in. carbons and current is led into the carbons at their upper ends, as is usual, there will be at the start a fall of voltage along the carbon due to 48 in. of carbon, which will gradually decrease as the carbons burn away. Apart from the loss of power which would occur at the beginning of the test, the voltage available at the arc itself will vary so much from the beginning to the end of the run that a satisfactory arc cannot be maintained throughout. One method which is used to overcome this difficulty is to construct the lamp so that a sliding contact is made to the carbons where they pass through the base-plate just above the economiser, in which case the amount of carbon between the contacts and the arc is small and constant. This method can only be said to have been partially successful, and the most satisfactory results have been obtained by methods which improve the conductivity of the carbons themselves. Of these there are two, providing the carbon with a metal core, and coppering the outside of the carbon. Coppering the carbon is quite satisfactory as a means of increasing its conductivity. It has not, however, been very successful with flame carbons, as although only a very light deposit of copper is put on, there is a tendency for the copper skin not to burn away but to project as a sheath over the point of the carbon, causing uneven and unsteady burning. In spite, therefore, of the fact that coppering is cheaper than providing the carbon with a metal core, coppered carbons are now less used than formerly, and seem likely in the course of time to be entirely superseded by metal-cored carbons.

In the metal-cored carbon the increased conductivity is obtained by threading a brass or zinc wire the length of the carbon and turning its upper end down the side of the carbon so that there may be direct electrical contact between the carbon holder and the wire. Originally zinc wires were used, but brass has been successfully substituted and is easier to deal with from the manufacturing point of view. At first this wire was simply threaded into the core canal, but it was soon

found that the end of the wire coming direct into the arc, as it did by this method, caused unsteady burning, partly because of the fusing and volatilising of the wire itself, and partly because of the disintegrating effects of these processes on the core. It is now therefore standard practice to run the wire in a separate channel; Fig. 1 shows on an enlarged scale the cross-section of a large-cored and a small-cored carbon provided with this separate channel, and it will easily be realised that the formation of this small hole increases the cost of tools and the difficulty of pressing the carbons, and thus raises their cost. The advantages gained are, however, considerable. The end of the wire never comes into the arc and the steadiness of burning is greatly enhanced. To obtain the best results the carbons should be placed in the lamp so that the wire is on the outside, away from the arc, but even without this precaution the disturbing effect of the wire is very slight; but the end of the wire as it fuses would be volatilised by the arc and a brown deposit formed on the economiser. It is most important to be sure with metal-cored carbons that direct contact is

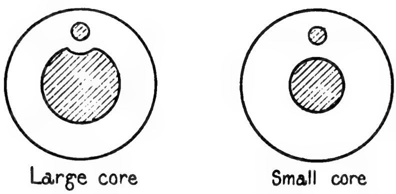


FIG. 1.- Cross-section of Metal-cored Flame Carbons.

made in the carbon-holder to the flattened end of the wire which is turned down the side of the carbon, as if the circuit—carbon-holder to carbon and carbon to wire—is relied upon the contact may be very poor and the benefit of the metal core largely lost. It is also most desirable that the wire should make good contact with the carbon throughout its length so that the end of the wire nearest the arc is always in electrical contact with the carbon at, or at least in very close proximity to, the actual tip of the carbon. This is obtained by various makers in various ways: one crinkles the wire, another provides it with excrescences or flattened portions every inch or less, a third fills the wire canal with a special conducting paste which holds the wire to the carbon; in some cases the wire canal is joined to the core canal so that the core runs into the wire canal, but this is not very good because the core in the wire canal exercises a disturbing influence on the burning, and if it completely surrounds the wire it insulates it from the carbon.

We come finally to the consideration of the composition of the core. Bremer's results indicated that the fluoride used as flame-producing material should be present to the extent of about 15 per cent. of the whole electrode. The efficiency of the arc can be increased by in-

creasing the percentage of fluoride; but other factors have to be taken into consideration, namely, rate of burning, steadiness of burning, and the conductivity of the electrode, all of which are affected unfavourably by increasing the percentage of fluoride beyond certain limits. The cores of the carbons manufactured by the author's company and those of other manufacturers which he has analysed will be found to contain about 50 per cent. of fluoride, the exact percentage varying slightly. This analysis is a very difficult one to make, and it requires considerable experience and special knowledge before reliable results can be obtained. The author thinks, however, that this figure may be regarded as more or less standard practice. The particular fluoride used depends on the colour it is desired to give to the arc. The golden-yellow

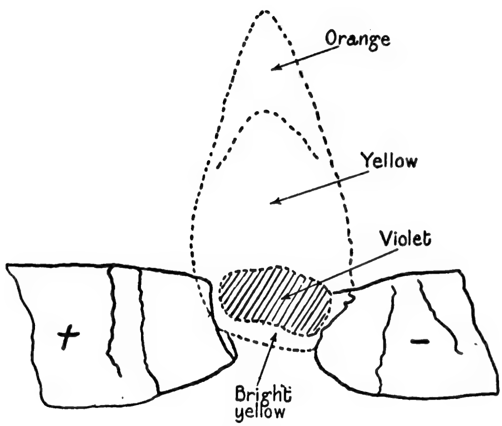


FIG. 2.—Arc between two Flame-cored Carbons.

arc—which is, of course, in most general use, and which alone is dealt with in this paper—is obtained from calcium fluoride, the white arc from cerium fluoride, and the red arc from strontium fluoride. Neither the white nor the red arc are nearly so efficient as the yellow, but increased efficiency may in these cases be obtained, with, of course, a slight sacrifice in purity of colour, by the substitution of calcium fluoride for part of the cerium or strontium fluoride. In all cases the core is made by mixing finely ground carbon and fluoride with a solution of potassium silicate and pressing this mixture into the core canal of the carbon and drying at a suitable temperature. The secret of successful coring lies more in the composition of the silicate solution used than in anything else, as potassium silicate is a very indefinite compound, the alkalinity of which may vary over wide limits.

It will be seen that with approximately 50 per cent. of fluoride in the core there will be 12½ per cent. of fluoride in a large-core carbon, and only 5½ per cent. in a small-core carbon.

If the image of a yellow flame arc be thrown on the screen it will be seen that there is a large yellow flame with a central violet core stretching from one carbon to the other. Around this core the intensity of the colour of the flame is greatly increased, and if a suitable image is obtained, the yellow flame can be seen separating the violet core from the tips of the carbons. In Figs. 2, 3, and 4 are shown drawings of yellow flame arcs between horizontal carbons using different carbon combinations. In Fig. 2 both carbons are flame-cored; in Fig. 3 the positive only, and in Fig. 4 the negative only. The drawings show that the yellow flame cannot be seen between the carbon tip and the core of the arc except when the carbon is flame-cored, and further, that the size of the flame whilst it depends on the total amount of fluoride in the pair of carbons is more dependent on the fluoride in the positive than in the negative carbon. Now it will be shown later that the additional

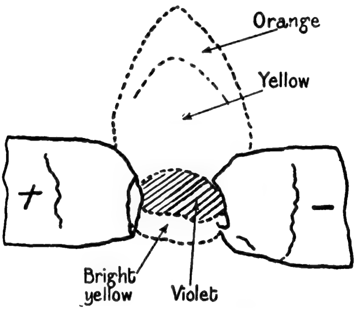


FIG. 3.—Arc between Positive Flame-cored and Negative Ordinary-cored carbon.

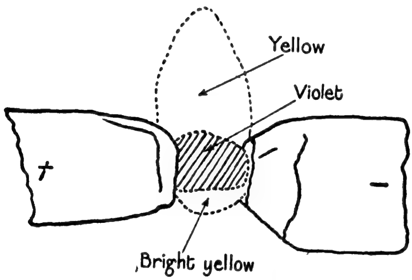


FIG. 4.—Arc between Positive Ordinary-cored and Negative Flame-cored Carbon.

efficiency due to the flame-producing material in the negative carbon is but slight and is accompanied by a decrease in the steadiness of the arc. Hence it has become common practice to use ordinary core in the negative carbon for direct-current arcs, and we arrive at a further subdivision of flame carbons into—

Flame-cored carbons

and—

Ordinary-cored carbons.

To summarise what has been written, it will be seen that flame carbons may be subdivided into two main groups :—

1. Large-core carbons.
2. Small-core carbons.

The second of these groups may be further subdivided into two groups :—

2a. Small-core flame-cored carbons.
2b. Small-core ordinary-cored carbons.

More simply taking these two classifications together we get three groups, thus :—

1. Large-core flame-cored carbons (L.C.F.).
2. Small-core flame-cored carbons (S.C.F.).
3. Small-core ordinary-cored carbons (S.C.O.).

The letters given in brackets will be used in this paper to indicate to which of these three groups the carbons used in the various tests belong. Manufacturers generally use reference numbers in their catalogues for the same purpose, but as these numbers vary from one manufacturer to another the above reference letters will be found more convenient for the present purpose. Further, any of the carbons in the above three classes may be either :—

1. Metal-cored (M.C.).
2. Coppered (Cop.).
3. Plain (P.).

Considerable space has been devoted to a full consideration of the classification of the standard flame carbons in use because great confusion exists amongst the carbon-buying public on the question. No doubt this is partly due to the fact that no paper dealing comprehensively with the subject has been published, the author being, so far as he knows, responsible for the only attempt at a complete classification so far published in English. The author's own experience is that the nearest the majority of arc-lamp users can approach to the correct ordering of carbons is to specify the particular make of lamp for which they are required, or else the external dimensions of the carbons, from which the manufacturer is left to determine the correct carbons to supply. This is by no means an easy matter on account of the number of classes and the variety of combinations which are used. The author recently ordered carbons from five manufacturers for a particular lamp specifying only the sizes of the carbons and the fact that they were to be plain, and found that he received as many combinations as there were manufacturers. For alternating current it is generally a fairly simple matter, as the two carbons are nearly always the same diameter and are both small-core flame-cored, and it only remains to decide whether metal-cored, coppered, or plain carbons are required. In direct-current lamps there is much greater variety; generally the positive carbon is 1 mm. larger in diameter than the negative, though exceptions exist to this rule. When the carbons are metal-cored the most general combination is a large-core flame-cored positive with a small-core ordinary-cored negative, but one also meets frequently the combination of two small-core flame-cored carbons, and occasionally even a large-core flame-core positive with a small-core flame-core negative, though this is probably the result of an actual mistake in the cases where it is found. When the carbons are either coppered or plain the most usual combination is two small-core flame-core carbons, though the use of a large-core flame-core positive and a small-core ordinary-core negative,

as with metal-cored carbons, is frequent and on the whole to be preferred. These combinations may be tabulated as given in Table II. (see page 741).

It is safe to say that only harm results from the variety of combinations in use, which is largely due to the desire of the arc lamp-maker to adopt a special type of carbon in the hope that in this way the carbon business resulting from the sale of his lamps will be secured to himself. This result rarely comes about, at any rate from this cause, as, sooner or later, the customer comes to the carbon manufacturer, who finds out what carbons are required, or at least the nearest of his own standard types. Instead, therefore, of the result hoped for, the more likely consequence is that the customer burns his lamp with a different combination than that for which it was originally adjusted, especially if the original carbons were in some way special. As a matter of fact, the real interests of the lamp-maker and the carbon-maker are alike. The former wants cheap carbons to help his lamp sales, and the latter wants standardisation to enable him to manufacture cheaply. This standardisation should apply not only to types and diameters but also to lengths. To give an example as regards the question of length: when the first flame lamps came over from the Continent they were constructed for 600-mm. carbons, which is equal to 23⅝ in. The English lamp-makers naturally made their lamps for 24 in.; carbon buyers, measuring the Continental carbons with an English rule, came to the conclusion that they were either 23½ in. or 23¾ in. long, and in a very short time one had people ordering four lengths—23½ in., 600 mm., 23¾ in., and 24 in.—when one length would have met all cases. It must be remembered also that in manufacturing the long thin carbons used in flame lamps there is necessarily a considerable output of broken and crooked carbons which can be used up in shorter lengths; it is therefore most distinctly to the interest of the maker of magazine lamps which require short carbons to construct his lamp to burn the same diameters and types as those used in lamps burning long lengths. Any lamp which requires special carbons and which cannot be used with the standard types is saddled with a permanent handicap.

Before leaving this section something must be said with reference to the Blondel carbon. This carbon has been developed by Professor Blondel with a view to obtaining the increased efficiency possible with higher percentages of fluoride. In type it is between a Bremer and a standard carbon. There is a very large central core with a very thin outer shell of pure carbon; in a 14-mm. carbon the core is 9 mm. in diameter, and occupies therefore nearly one-half of the area. If such a core contains 50 per cent. of fluoride, it means that the whole electrode contains nearly 25 per cent. of fluoride instead of only 12½ per cent., as in the standard large-core carbon. The gain in efficiency is not, however, so great as these figures might lead one to expect, as figures which will be given later will show. With only 50 per cent. of fluoride in the Blondel core, the efficiency is about the same as with standard flame carbons, but the percentage of fluoride can be increased in the Blondel

core to 60 per cent., or even more without producing unsteady burning, when a distinct gain in efficiency is obtained. This is apparently mainly due to the use of a larger diameter carbon, in consequence of which the crater does not cover the whole of the tip, and the amount of fluoride coming into the arc is not increased unless the percentage of fluoride in the core mixture is increased. The core of the Blondel carbon is of different composition to the standard flame core, containing in addition to the fluoride and silicate a certain percentage of borates; it may be made in the same way as the original Bremer carbons in the form of a solid rod which is inserted, either before or after baking, into the outer shell; shell and core can also be pressed simultaneously.

Reference may also be made to the special carbons used in the Jandus enclosed flame lamp, but as these have no general application they need not be considered in detail.

Rate of Consumption and Steadiness.

The one test that seems to be of supreme interest to the English carbon user is the rate of carbon consumption. For the last 10 or 15 years it has been possible by the use of high-grade carbons in open type lamps to increase the efficiency of the arc by about 25 per cent. with a diminution of only about 15 per cent. in the burning hours, and an increase of about 4 per cent. in the carbon cost. The writer doubts whether there is 1 per cent. of the lighting authorities, company or municipal, or of the large consumers, such as railways or dockyards, who has not and does not still prefer the longer burning hours of the low-grade carbons. There was naturally, therefore, considerable outcry at first at the high rate of consumption and high cost of flame carbons, and it required several years' work before the carbon-using public was convinced that the extra cost was more than justified by the increased efficiency. Nowadays, thanks largely to the real competition of high-pressure gas, and to the imagined competition of high candle-power metal-filament lamps, engineers are paying more attention to the cost per candle-hour than simply to the carbon cost.

The rate of burning of flame carbons varies somewhat more from one batch to another and from one make to another than does the rate of burning of open-type carbons. This is partly a secondary effect of the economiser: if the carbons give a rather short arc the points will be low in the economiser, and the carbons will burn away more rapidly. The differences are not more than about 10 per cent., and the figures given in Table III. may be taken as fairly typical.

The rate of consumption also varies in different makes of lamp, but the figures given in Table III. are representative, and for general practical purposes the carbons may be taken as burning at the rate of approximately 30 mm. per hour. That means that 600-mm. carbons, allowing for 75-mm. unburnt ends, will give a life of 17 to 18 hours with one trim. It is difficult to work out actual carbon costs, as the prices at which consumers buy vary so greatly according to the quantities purchased, but if we take discounts of 45 per cent. off list for metal-cored carbons and

50 per cent. off list for plain carbons as fairly representative prices for the largest consumers, we arrive at the costs in Table IV. The figures in this table are worked out on the assumption that 24-in. metal-cored and 12-in. plain carbons are used. The carbon cost will be slightly higher the shorter the carbons used in the lamp, as the unburnt end is a higher percentage of the whole. The figures given in this table will be reduced to costs per 1,000 candle-hours when the candle-power measurements have been considered.

Table III.

Rate of Burning of Carbons in Direct-current Excello Lamps.

Current.	Positive Carbon.	Negative Carbon.	Consumption of each Carbon per Hour.
6 amperes	8 mm. L.C.F., M.C.	7 mm. S.C.O., M.C.	30 mm.
8 ,,	9 ,, ,, ,,	8 ,, ,, ,,	29 ,,
10 ,,	10 ,, ,, ,,	9 ,, ,, ,,	29 ,,
12 ,,	11 ,, ,, ,,	10 ,, ,, ,,	27 ,,

Table IV.

Carbon Cost in Pence per Hour for various Currents.

Current.	Metal-cored Carbons.	Plain Carbons.
6 amperes	0·181	0·126
8 ,, ...	0·206	0·144
10 ,, ...	0·228	0·160
12 ,, ...	0·256	0·181

The steadiness of burning of flame carbons has been very greatly improved during the last three or four years, and so far as any visible effects are concerned the arc is practically, if not quite, as steady as the open type arc. Occasionally flickers and fluctuations of the light do occur, but not to any great extent. If a sensitive recording ammeter is connected in series with the arc remarkably good records are obtained. A typical curve is given in Fig. 5, which is for an 8-ampere Excello lamp. Mention has already been made of the fact that calcium fluoride in the negative carbon causes unsteadiness, and

this may be illustrated by the curves in Figs. 6 and 7, which show for the same lamp the record with an ordinary-cored and with a flame-cored negative, the positive carbon being the same in each case and all the carbons of the same make.

Candle-power Measurements.

Before giving the results of candle-power tests, it will be well to describe the methods of photometry adopted. The photometer-room

Fig. 5.—Recorder Curve for Carbons in Excello Lamp.

of the General Electric Company's Carbon Works' Laboratory is a large narrow room 54 ft. by 10 ft., entirely without windows and with blackened walls and ceiling. At one end of this is fixed an upright standard carrying two large circular mirrors which can be rotated around a horizontal axis and fixed in position at any desired angle. These mirrors are fixed at an angle of 45° to the radius of their circle

Fig. 6.—Recorder Curve for Arc with Ordinary-cored Negative Carbon.

of rotation and reflect the light from the arc, which is hung at the centre of rotation up the room to the photometer bench. A Lummer-Brodhun photometer head is used, and as comparison lamp an ordinary carbon filament lamp which is standardised in English candles against N.P.L. standards. The colour match on the photometer screen is

Fig. 7.—Recorder Curve for Arc with Flame-cored Negative Carbon.

fairly good with yellow flame arcs, and it is quite easy with a little practice to obtain the position of balance.

In order to obtain a distribution curve readings of the candle-power are taken every 10° throughout a vertical plane. The arc is centred with the plane of the carbons parallel to the photometer screen. Both mirrors are used at once, one on each side of the arc so

as to average the two rays in opposite directions ; readings are taken as far above the horizontal as possible and carried down to the 90° angle, *i.e.*, vertically below the arc ; at the last three positions, 70°, 80°, and 90°, only one mirror can be used at a time, and the measurement

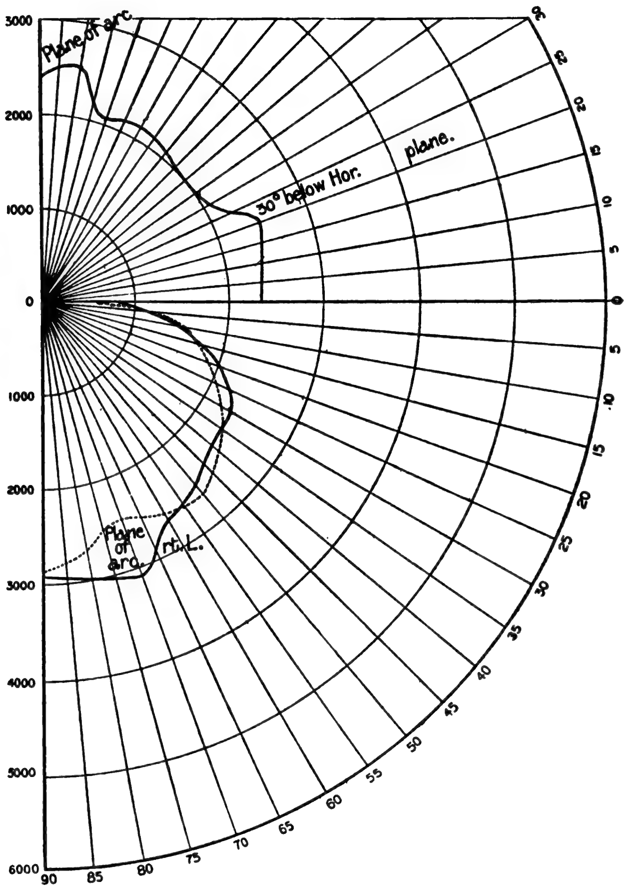


FIG. 8.—Distribution Curves for Flamgold Lamp in Plane of Carbons and Plane at right angles to Carbons.

at the last position presents special difficulty with metal-cored carbons, as drops of molten metal are liable to fall on the mirror. At each position four readings of the photometer are taken in as rapid succession as possible to eliminate the effect of any sudden variations in the arc ; a complete set of readings is taken in this way, and then the whole process is repeated three times, thus giving sixteen readings for each

position. This gives the distribution curve for the light in the plane of the carbons; the lamp is now rotated round its vertical axis through an angle of 90°, and the whole process is repeated to obtain the distribution curve in the plane at right angles to the carbons. In Fig. 8 are shown these two curves for a 9-ampere Flamgold lamp without globes, the dotted curve representing the distribution in the plane of

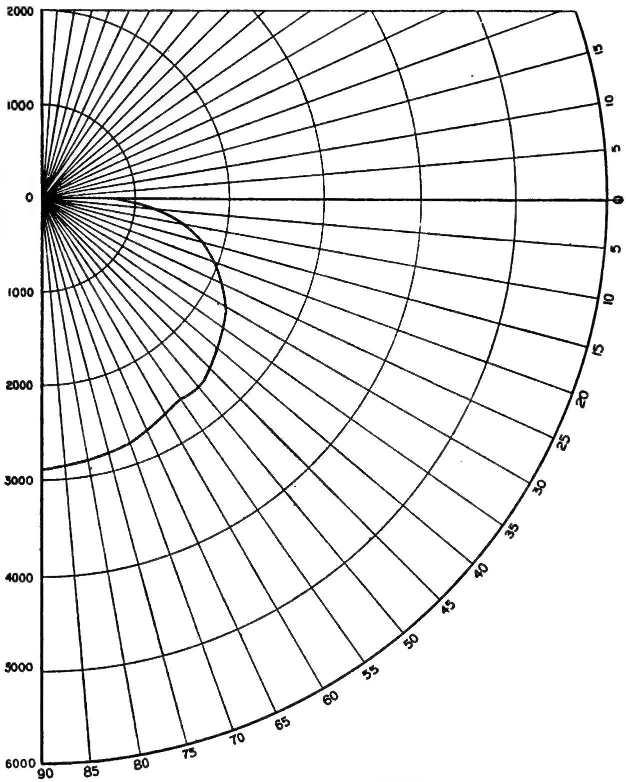


FIG. 9.—Distribution Curve for 9-ampere Flamgold Lamp.

the carbons and the full curve in the plane at right angles to the carbons. In the upper part of this figure is given the curve of horizontal distribution for the same lamp for the cone of rays making an angle of 30° with the horizontal. The data for this test are given in Table V.

It will be seen that the difference is slight between the two planes whether in distribution or spherical candle-power. It has not been thought necessary to reproduce the two curves in the remaining figures, but instead the average of the two sets of readings has been taken at

TABLE V.

Comparison of Candle-power in Plane of Carbons and Plane at Right Angles to Carbons. Flamgold Lamp. No Globe.

Carbons.	Plane.	Amperes.	Arc Volts.	Watts.	Mean Spherical.		Lower Hemispherical.	
					C.P.	W./C.P.	C.P.	W./C.P.
Positive— 9 mm. L.C.F., M.C.	Of carbons ...	9	41	369	1,074	0·344	2,120	0·174
Negative— 8 mm. S.C.O., M.C.	Right angles	9	41	369	1,126	0·328	2,158	0·172
	Mean ...	9	41	369	1,100	0·336	2,139	0·173

TABLE VI.

Test Results for Excello Lamps. No Globes.

Carbons.			Amperes.	Arc Volts.	Watts.	Mean Spherical.		Lower Hemispherical.	
Make.	Positive.	Negative.				C.P.	W./C.P.	C.P.	W./C.P.
A	8 mm. L.C.F., M.C.	7 mm. S.C.O., M.C.	6	44·0	264	778	0·340	1,430	0·185
	9 ,, ,, ,,	8 ,, ,, ,,	8	44·5	356	1,092	0·326	2,035	0·175
	10 ,, ,, ,,	9 ,, ,, ,,	10	45·0	450	1,627	0·276	3,087	0·145
	11 ,, ,, ,,	10 ,, ,, ,,	12	47·0	564	1,895	0·297	3,425	0·164
B	8 mm. L.C.F., M.C.	7 mm. S.C.O., M.C.	6	44·0	264	696	0·380	1,307	0·202
	9 ,, ,, ,,	8 ,, ,, ,,	8	44·5	356	1,125	0·316	2,032	0·175
	10 ,, ,, ,,	9 ,, ,, ,,	10	45·0	450	1,630	0·276	3,052	0·147
	11 ,, ,, ,,	10 ,, ,, ,,	12	48·0	576	2,015	0·286	3,557	0·162

each position. This average curve for the above test is given in Fig. 9, and the data are included in Table V. As each point in each set of readings is the average of 16 actual photometer measurements, the final figure taken is the average of 32 measurements, and each distribution curve represents the result of between 350 and 400 photometer readings. The curves may therefore be regarded as representing with considerable accuracy the typical distribution, eliminating as far as possible sudden or erratic variations. The large number of readings taken accounts for the smoothness of the distribution curves; though the actual readings are not marked on the curve, every curve has been drawn with the greatest care to pass through all the recorded points.

To maintain the arc as steady as possible throughout the tests it is run in series with an enclosed lamp specially designed by Mr. Angold, of the General Electric Company, which keeps the current practically constant; the current is, of course, continually observed and adjusted by means of series resistances, if necessary. It is desirable that the current should be kept constant all the time and not merely have the desired value when the actual reading is taken, as otherwise the carbons do not burn to quite the right shape. The lamps are made to feed by hand after every second position, *i.e.*, after every 8 photometer readings; if the lamp is allowed to feed automatically the periods between the feeds are longer and there is a cyclical variation in the current and candle-power. The method of hand-feeding eliminates this and keeps the current up to full value; the voltage is in consequence perhaps a trifle higher than would be found in actual practice. Readings of voltage are also taken every second position and averaged for the whole test, the voltage across the carbons being read, thus eliminating any resistance in the lamp.

From the readings the polar and Rousseau curves are plotted, and the values of mean spherical candle-power and mean lower hemispherical candle-power obtained by planimeter measurement of the area of the Rousseau figure. Only the polar curves are given here, and it is not possible on the scale of these figures to show in most cases the distribution above the horizontal, which is, of course, slight. On the Rousseau figure this shows distinctly. The curves are plotted on special lithographed sheets, one of which is reproduced on a reduced scale in Fig. 10; the actual sheet measures 25 in. × 20 in.; so far as I know, there is no suitable paper on the market for plotting these curves, and this sheet is reproduced, as it may be useful to other experimenters. It is lithographed on thin Bristol board, and the curves can be plotted and the planimeter run over the Rousseau figure in a very short time.

In making comparative tests to investigate some particular point, as, for example, the comparison in two planes already given, the greatest care is taken to use carbons baked and cored at the same time, so as to eliminate manufacturing variations. As our investigations at Witton are naturally concerned chiefly with carbon questions, the great majority are carried out on the bare arc, though in some cases globes

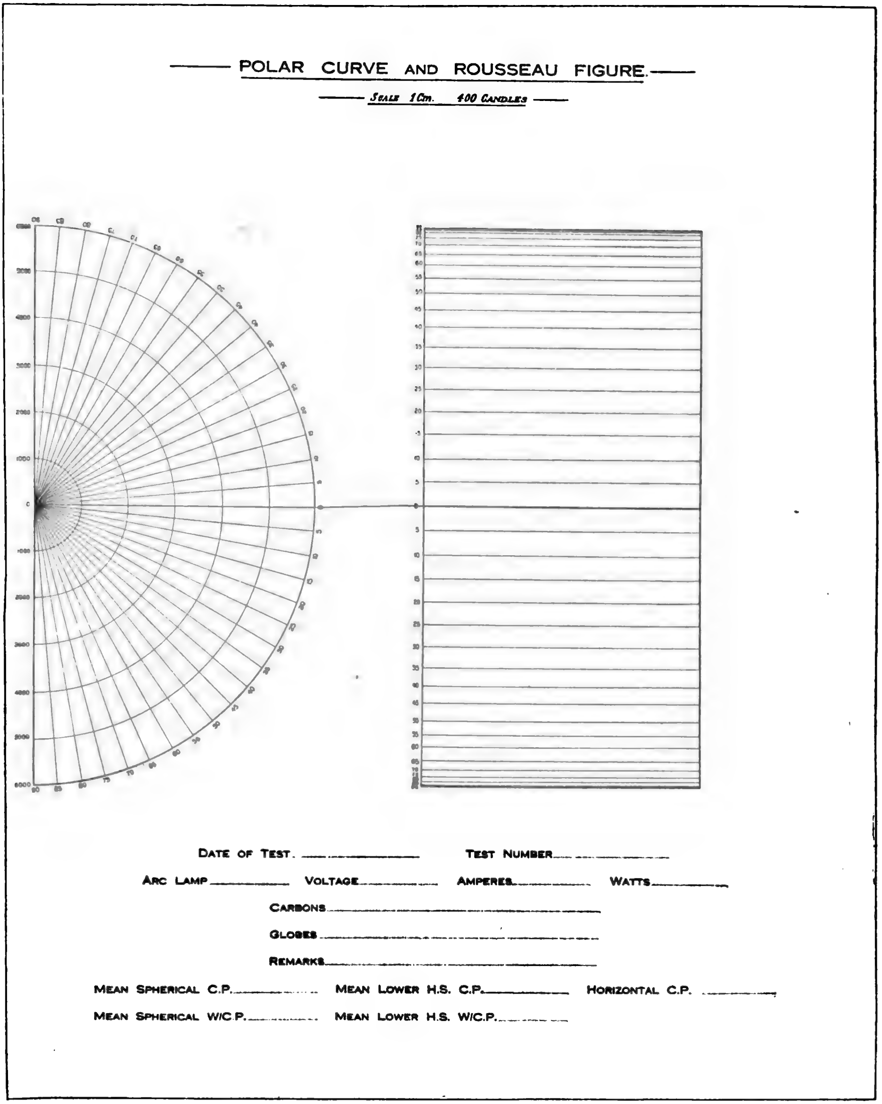


FIG. 10.—Curve Paper used for plotting Distribution Curve and Rousseau Figure.

have to be used; most of the curves in this paper are therefore for lamps without globes.

Test Results.

Candle-power and Lamp Current.—In Figs. 11 and 12 are given the distribution curves for four different Excello lamps, 6-, 8-, 10-, and 12-ampere respectively, and for two different makes of carbons. The data from these tests are given in Table VI.

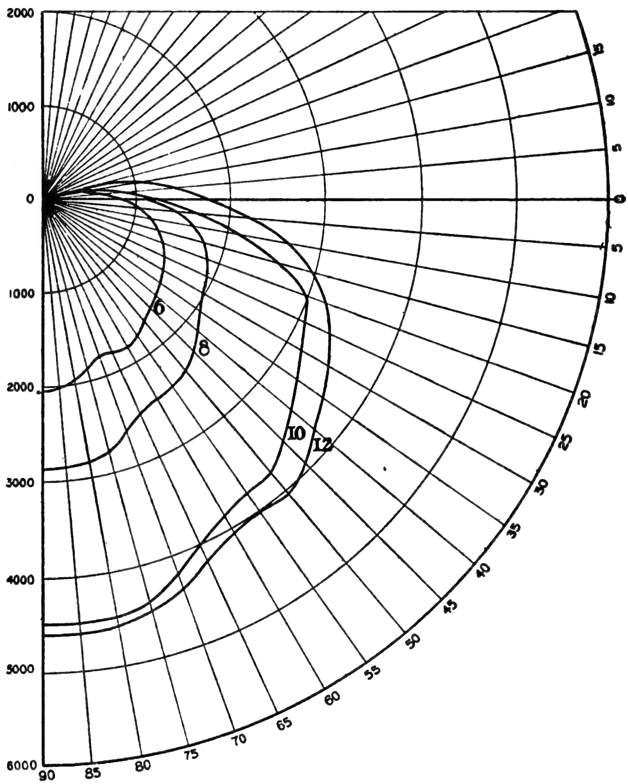


Fig. 11.—Distribution Curves for Excello Lamps. No Globes.

It will be seen that there is very little difference between the two different makes; the table also shows that there is not any great difference between the efficiency obtained at the various currents, except that there is a slight falling off at 6 amperes.

A second series of tests on the same point was made with Angold magazine lamps, but in this case the tests were made with the standard globes supplied with these lamps for street-lighting. These

are an inner and outer clear globe, the shape of the inner globe being specially designed so as to deviate the course of the rays into the angles most useful for outdoor lighting. The distribution curves obtained for 7-, 8- and 10- ampere lamps are given in Fig. 13, and the test results in Table VII. It will be noticed on comparing these curves with that in Fig. 20, that the globes reduce the light between the angles from 60°

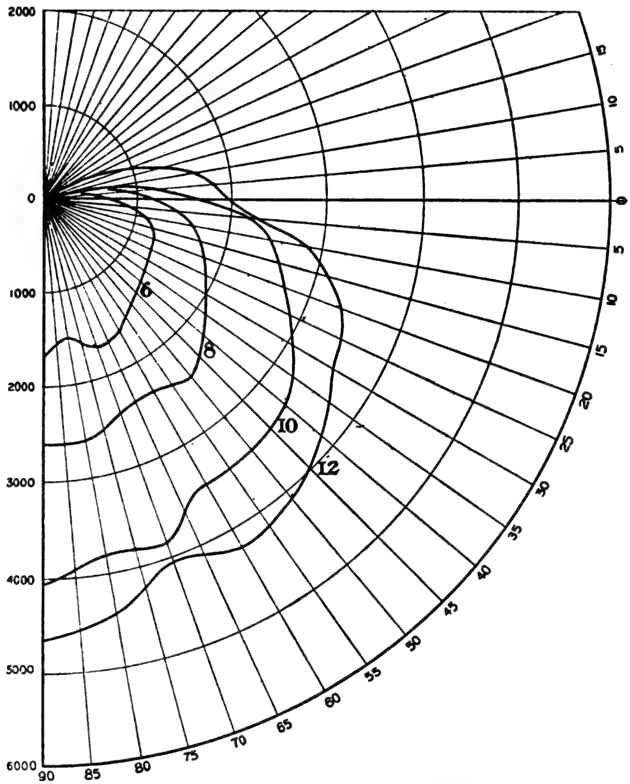


FIG. 12.—Distribution Curves for Excello Lamps. No Globes.

to 90° below the horizontal, part of this reduction being due to the shadow of the ashpan; the radiation between the angles 15° to 60° is relatively increased. The test results confirm those obtained from the Excello lamps in showing a slight gain in efficiency with the higher currents.

Candle-power and Current.—It is of interest to test the effect of current on candle-power using the same size carbons, and an experiment to determine this was carried out with an Excello lamp. An 8-ampere Excello lamp was used with 9-mm. and 8-mm. carbons, *i.e.*, the

TABLE VII.

Test Results for Angold Magazine Lamps. Standard Inner and Outer Clear Globes.

Carbons.			Amperes.	Arc Volts.	Watts.	Mean Spherical.		Lower Hemispherical.	
Make.	Positive.	Negative.				C.P.	W./C.P.	C.P.	W./C.P.
B	8 mm. L.C.F., P.	7 mm. S.C.O., P.	7	42·0	294	896	0·328	1,710	0·172
	8 ,, ,, ,,	7 ,, ,, ,,	8	43·5	348	1,114	0·312	2,112	0·165
	9 ,, ,, ,,	8 ,, ,, ,,	10	43·0	430	1,471	0·292	2,825	0·152

TABLE VIII.

Effect of Current on Candle-power and Efficiency. Excello 8-ampere Lamp. No Globes.

Carbons.			Amperes.	Arc Volts.	Watts.	Mean Spherical.		Lower Hemispherical.	
Make.	Positive.	Negative.				C.P.	W./C.P.	C.P.	W./C.P.
B	9 mm. L.C.F., M.C.	8 mm. S.C.O., M.C.	6	44·6	267·6	547	0·489	1,040	0·257
			8	44·2	353·6	919	0·385	1,670	0·211
			10	44·4	444·0	1,422	0·312	2,587	0·171

correct size carbons for the lamp, and was run with a 6-, 8-, and 10-ampere arc, the mechanism being shunted in the last and the arc in the first case, so that 8 amperes was always passing through the lamp series coils. It was intended to carry the test up to 12 amperes, but the arc was so unsteady at this current that the curve could not be obtained.

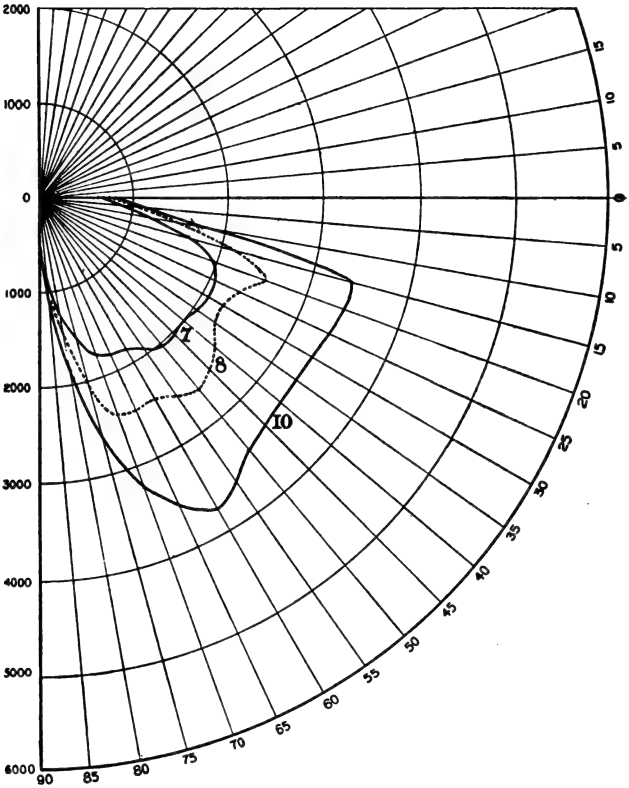


FIG. 13.—Distribution Curves for Angold Magazine Lamp with Inner and Outer clear Globes.

The distribution curves are given in Fig. 14, and the results summarised in Table VIII.

The table shows, as was to be expected, that the efficiency increases with the current; the number of measurements is not sufficient to draw a curve connecting current with watts per candle, but the rate of increase apparently decreases as the current rises, and, as is shown by the 12-ampere test, a limit is put by other considerations; of course, also, the rate of consumption of the carbons increases rapidly when they are overrun.

Candle-power and Voltage.—Another point of interest to investigate is the effect of arc voltage on the candle-power and efficiency. A test was carried out in a 10-ampere Angold Magazine lamp, which was hand-fed to keep the voltage constant at 38, 42, and 47 volts respectively. The distribution curves are given in Fig. 15, and the test results in Table IX. These figures show that although the candle-power rises

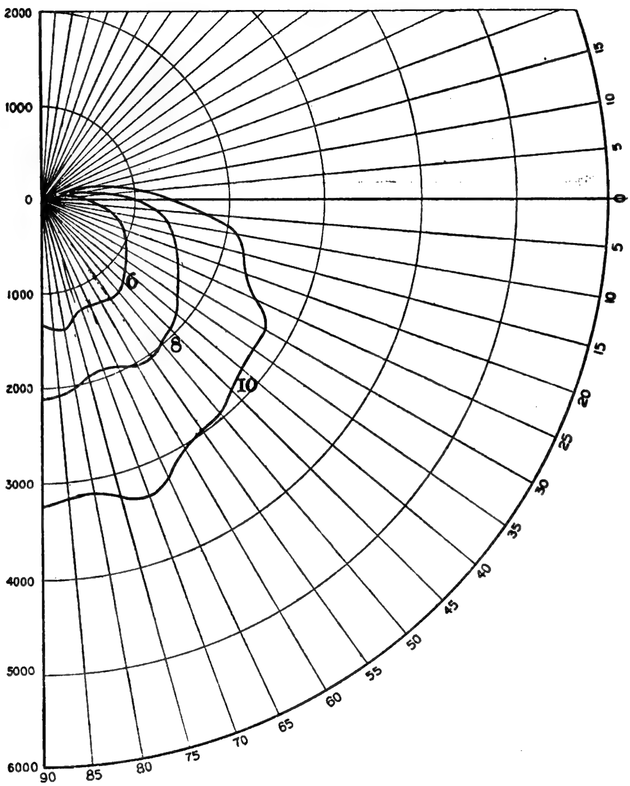


FIG. 14.—Distribution Curves showing effect of Current.

with the voltage the efficiency falls though the differences are not very great.

Carbons of different Makes.—A comparison of two different makes of carbons in Excello lamps has already been given; it was intended to carry out a more comprehensive test, covering all the leading carbon manufacturers, and for this purpose carbons were ordered for the Angold magazine lamp from five different makers. As has been mentioned already, each maker supplied a different combination, so that the original intention of the test is somewhat spoiled; it is, how-

ever, valuable as showing up the effect of using different combinations, and to make it more complete in this respect further carbons were obtained from two of the makers. The distribution curves are given in Figs. 16, 17, and 18, and the results summarised in Table X., in which are included the rates of consumption of the various carbons.

Several interesting points are brought out by this table. It will be noticed by comparing curves *a* and *c* with curves *b* and *d* that intro-

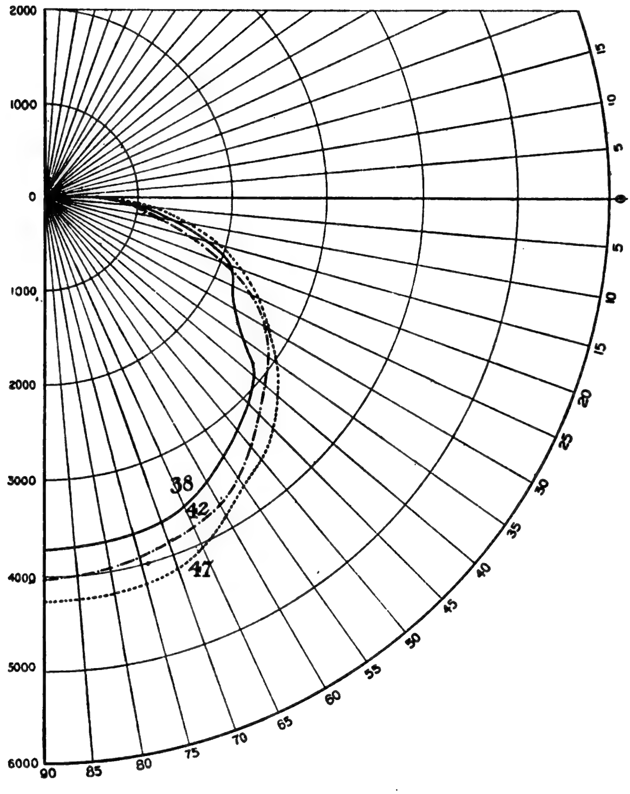


FIG. 15.—Distribution Curves showing effect of Voltage.

ducing flame material into the core of the negative carbon but still using a large-core flame-cored positive gives an appreciable improvement in both the candle-power and efficiency. It has, however, been pointed out that this advantage is accompanied by a loss in steadiness, as will be seen by again referring to the records in Fig. 6, which are for the carbons of make B, used to obtain curves *c* and *d*. It will be seen also that in the case of make A carbons the consumption was increased, whereas in the case of make B it was diminished by the alteration in

TABLE IX.

Effect of Voltage on Candle-power and Efficiency. Angold Magazine 10-ampere Lamp. No Globe.

Carbons.			Amps.	Arc Volts.	Watts.	Mean Spherical.		Lower Hemispherical.	
Make.	Positive.	Negative.				C.P.	W./C.P.	C.P.	W./C.P.
A	9 mm. L.C.F., P.	8 mm. S.C.O., P.	10	38	380	1,239	0·307	2,430	0·156
			10	42	420	1,289	0·326	2,535	0·166
			10	47	470	1,356	0·347	2,670	0·176

TABLE X.

Comparison of Carbons of different Makes and different Combinations. Angold Magazine 10-ampere Lamp. No Globes. Plain Carbons.

Figure.	Carbons.			Amps.	Arc Volts.	Watts.	Total Consumption, mm. per Hour.	Mean Spherical.		Lower Hemispherical.	
	Make.	Positive.	Negative.					C.P.	W./C.P.	C.P.	W./C.P.
16*a*	A	9 mm. L.C.F.	8 mm. S.C.O.	10	44·5	445	60·5	1,449	0·307	2,837	0·157
16*b*	A	9 ,, ,,	8 ,, S.C.F.	10	42·5	425	63·7	1,701	0·250	3,307	0·128
17*c*	B	9 ,, ,,	8 ,, S.C.O.	10	43·5	435	66·3	1,389	0·313	2,725	0·159
17*d*	B	9 ,, ,,	8 ,, S.C.F.	10	44·0	440	62·8	1,655	0·266	3,235	0·136
18*e*	C	9 ,, S.C.F.	8 ,, L.C.F.	10	43·0	430	65·6	1,274	0·338	2,497	0·172
18*f*	D	9 ,, L.C.F.*	8 ,, S.C.F.*	10	42·7	427	58·3	1,481	0·288	2,860	0·149
18*g*	E	9 ,, S.C.F.	8 ,, S.C.F.	10	43·0	430	67·2	1,365	0·315	2,662	0·161

* The cores of these carbons are smaller than normal, but they have been classified to the nearest corresponding size.

the core of the negative carbon. It is perhaps a matter of opinion which combination is to be preferred, but the author considers that the gain in efficiency is not worth the extra unsteadiness, added to which the combination of the two flame-cored carbons would be more expensive.

The combination of two small-core flame-cored carbons is illustrated by curve 18*g*; curve 18*f* may be looked upon as a hybrid between this

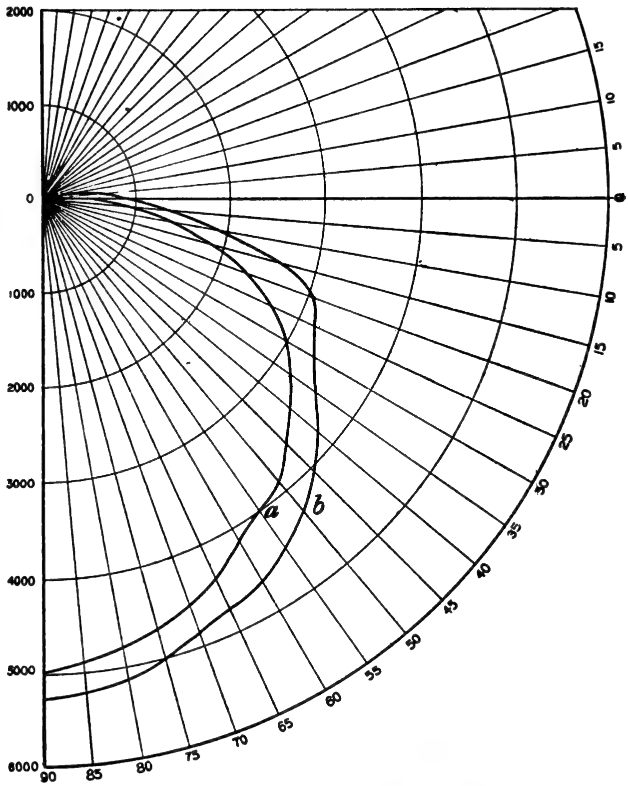


FIG. 16.—Distribution Curves for Angold Magazine Lamp. Carbons make A.

combination and the combination of a large-core flame-cored positive with a small-core flame-cored negative. The figures for curve 18*g* give no reason to prefer this, the most usual combination with plain flame carbons, over the combination in tests 16*a* and 17*c*, which corresponds to common practice with metal-cored carbons, and which the author thinks should be standard. The test results from curve 18*f* are remarkably good and the recorder curve was very steady, which

was rather surprising as the carbons are of a little-known make. The manufacturer C, who supplied a small-core carbon for the positive and a large-core carbon for the negative, hit upon a most original combination. Probably he (or his agent) did not trouble about the matter at all, and simply sent the first carbons of the correct diameter and length which he could lay his hands on ; if so, he has reaped a just reward by

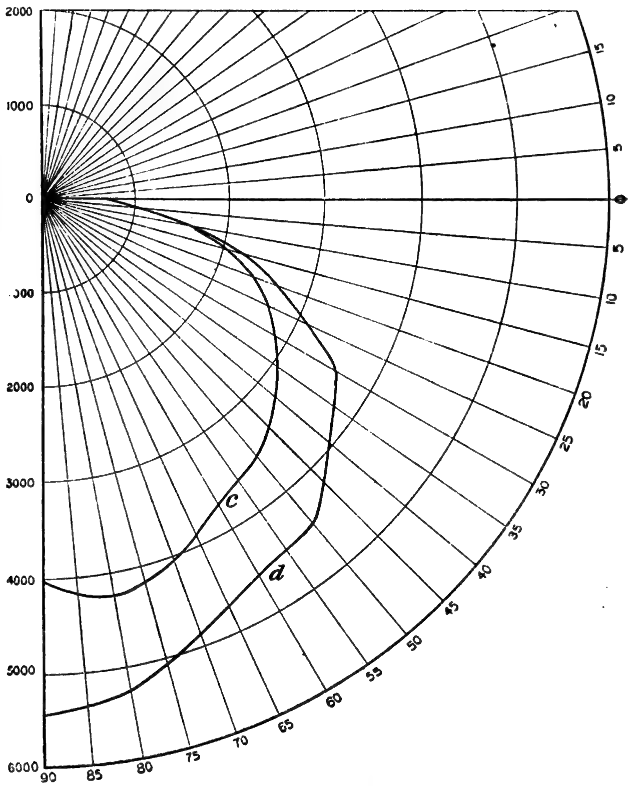


FIG. 17.—Distribution Curves for Angold Magazine Lamp. Carbons make B.

attaining the lowest efficiency and unsteadiest burning of the series. This case illustrates the confusion which must result from lack of standardisation.

Comparison of different Lamps.—It would hardly be possible to obtain distribution curves for all the different flame arc lamps on the market, and it is fairly certain that the immense amount of labour which such a proceeding would involve would be but poorly repaid, as lamps which do not differ in principle and which use carbons of the

same type may be assumed with some certainty to have approximately similar distribution curves and efficiency. It would be another matter perhaps if the lamps were all tested with the globes and coronas which the makers supply; but this would open up a much wider subject, and one which is better approached from a different standpoint, which will be referred to presently. There are, however, certain groupings into

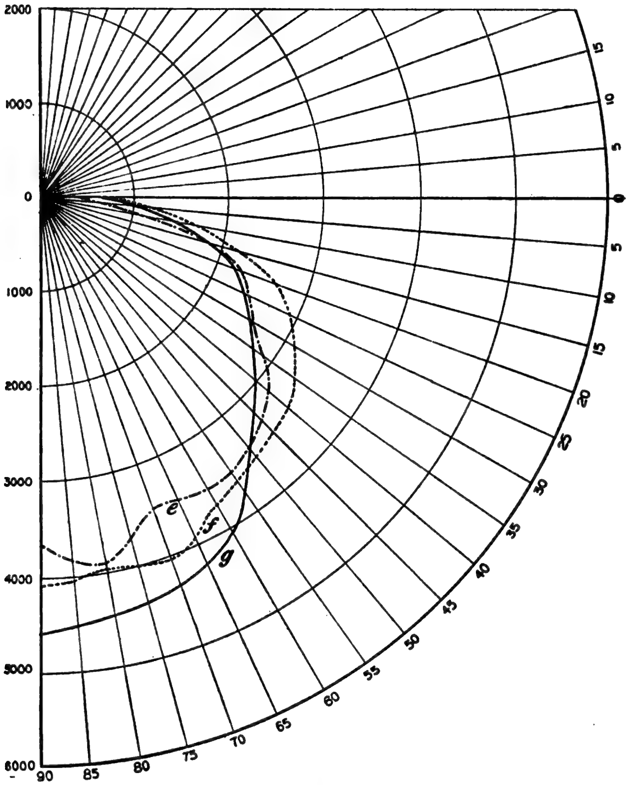


FIG. 18.—Distribution Curves for Angold Magazine Lamps. Carbons makes C, D, and E.

which existing flame lamps fall, and it seemed worth while to test representative examples of these groups. There is first the simple single carbon flame lamp, *i.e.*, a lamp with one pair of carbons only, of which group the Excello is the leading example. Tests of the Excello lamp have already been given, but the distribution curve of the 10-ampere lamp is repeated in Fig. 19, and the test results in Table XI.

Secondly, we have the magazine lamps of which group the Angold magazine lamp may be taken as representative; the distribution curve

for this lamp is given in Fig. 20, and the test results in Table XI. It will be seen by a comparison of these results with those for the Excello lamp that both in distribution and efficiency there is not very much to choose between the two, and that the advantages for street lighting which the magazine type possesses can be obtained without any material sacrifice of either of these properties.

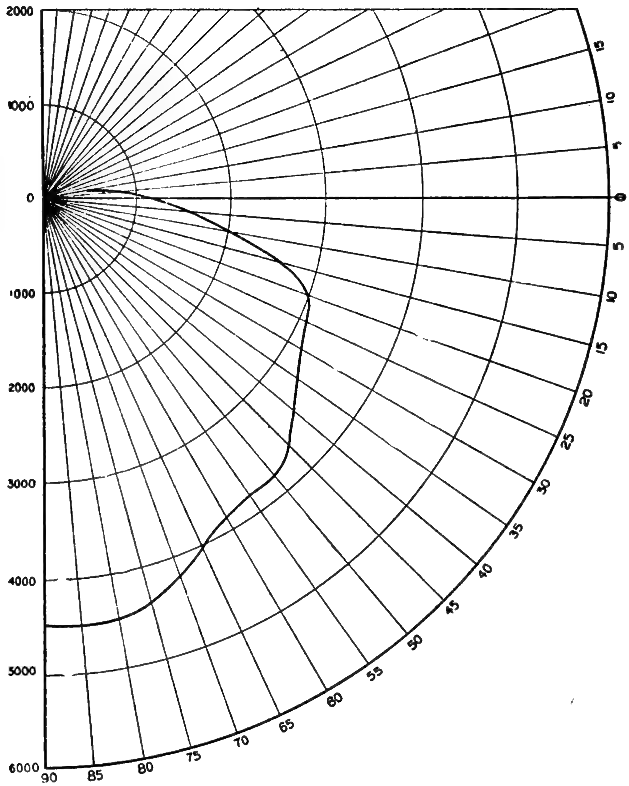


FIG. 19.—Distribution Curve for 10-ampere Excello Lamp. No Globe.

Thirdly, there is the group of special lamps which have certain unique features, and of these the only two of importance are the Jandus enclosed flame lamp and the Crompton-Blondel lamp, distribution curves for which are given in Figs. 21 and 22. The Jandus lamp was of necessity tested with the inner chimney, and the carbons used were those supplied by the makers and are altogether of special construction; the curve is difficult to obtain, as the arc wanders considerably and the current varies from 5 to 6 amperes, the voltage varying from 60 to 70 volts. The carbons are vertically one above the other, and the arc is in the

centre of the globe, so there is considerable radiation above the horizontal; consequently the comparison on the basis of lower hemispherical candle-power is unjust to this lamp, as in practice reflectors would be used to utilise the light in the upper hemisphere. The comparison on the basis of mean spherical candle-power is a truer criterion of the value of this lamp; although the lamp does not stand high in this respect, the long carbon life must be remembered, and it is probable that in any enclosed

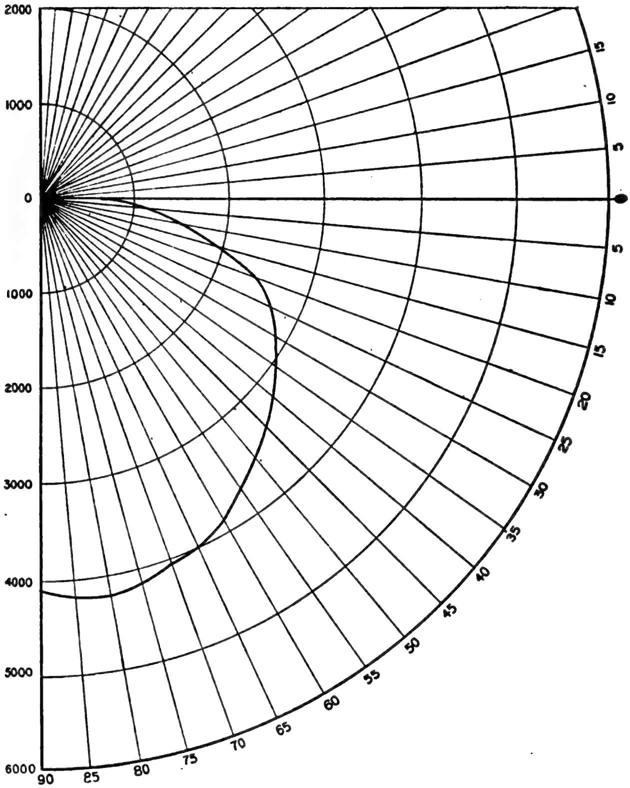


FIG. 20.—Distribution Curve for 10-ampere Magazine Lamp. No Globe.

flame lamp efficiency will have to be sacrificed to this end just as it has to be sacrificed in pure carbon lamps when an enclosed arc is used. In the Crompton-Blondel lamp the carbons are also arranged vertically, the positive flame carbon being the lower one; but an economiser is used, the negative carbon just projecting into it, so the distribution is nearly all below the horizontal and the curve is similar to that of an inclined carbon lamp except where the shadow of the lower carbon cuts off the light between the angles of 60° and 90°. The lamp will be dealt with

Table XI.

Comparison of different Types of Lamp.

Fig.	Lamp.	Globe.	Carbons. Make.	Carbons. Positive.	Carbons. Negative.	Amps.	Arc Volts.	Watts.	Mean Spherical. C.P.	Mean Spherical. W./C.P.	Lower Hemispherical. C.P.	Lower Hemispherical. W./C.P.
19	Excello ...	None ...	A	10 mm. L.C.F., M.C.	9 mm. S.C.O., M.C.	10·0	45·0	450·0	1,627	0·276	3,087	0·145
20	Angold Magazine	None ...	B	9 mm., L.C.F., P.	8 mm. S.C.O., P.	10·0	43·5	435·0	1,389	0·313	2,725	0·159
21	Jandus ...	Chimney only	Special Jandus carbons.			5·5	65·0	357·5	779	0·458	955	0·374
22	Crompton-Blondel	None ...	—	14 mm. Blondel	9 mm. cored, open type	10·0	39·6	396·0	2,231	0·178	4,177	0·095

Table XII.

Long-hour Test of Angold Magazine Lamp. Clear Inner and Outer Globes.

Carbons: Make B. Positive, 9 mm. L.C.F., P. Negative, 8 mm. S.C.O., P.

Hours Run.	Amps.	Arc Volts.	Watts.	Mean Spherical. C.P.	Mean Spherical. W./C.P.	Lower Hemispherical. C.P.	Lower Hemispherical. W./C.P.
0	10	43	430	1,471	0·292	2,825	0·152
25	10	43	430	1,439	0·299	2,725	0·158
50	10	43	430	946	0·455	1,812	0·237
100	10	43	430	860	0·500	1,602	0·268
125	10	43	430	605	0·711	1,130	0·381

more fully presently, but it is interesting to draw attention to the very high candle-power and efficiency obtainable with this type of carbon.

In connection with the use of magazine lamps a point of some importance arises. The object of the magazine lamp is to save carbon and trimming costs. Carbon costs are saved by the use of short plain carbons instead of long carbons, which must be either coppered or

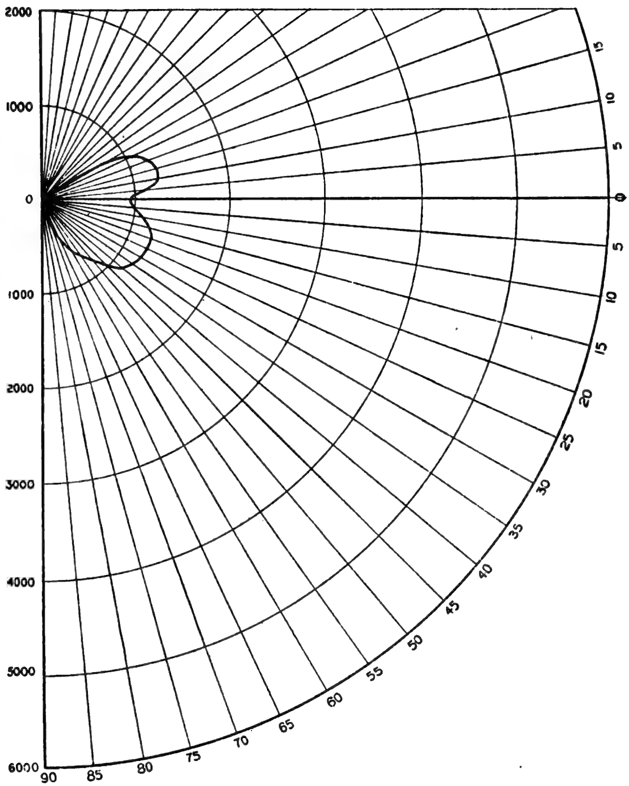


FIG. 21.—Distribution Curve for Jandus Regenerative Lamp. Inner Chimney only.

metal-cored. Trimming costs are saved by the long burning hours obtained with one filling of the magazine, and of late there has been a tendency to push this advantage to what seems to the author to be inordinate lengths. During the burning of the carbons deposit forms both on the economiser and the globe, and though with well-ventilated lamps the deposit on the globe may be very small, that on the economiser cannot be entirely prevented unless the principle of the enclosed lamp be resorted to. It is obvious that there is not much use in

prolonging the interval between trims beyond the limits set by the falling off in candle-power due to the formation of this deposit. A test was carried out on an Angold magazine lamp to see how great this was, and distribution curves are given in Fig. 23 and test results in Table XII. Standard inner and outer globes were used, and neither the globes nor economiser were cleaned during the test, but the maga-

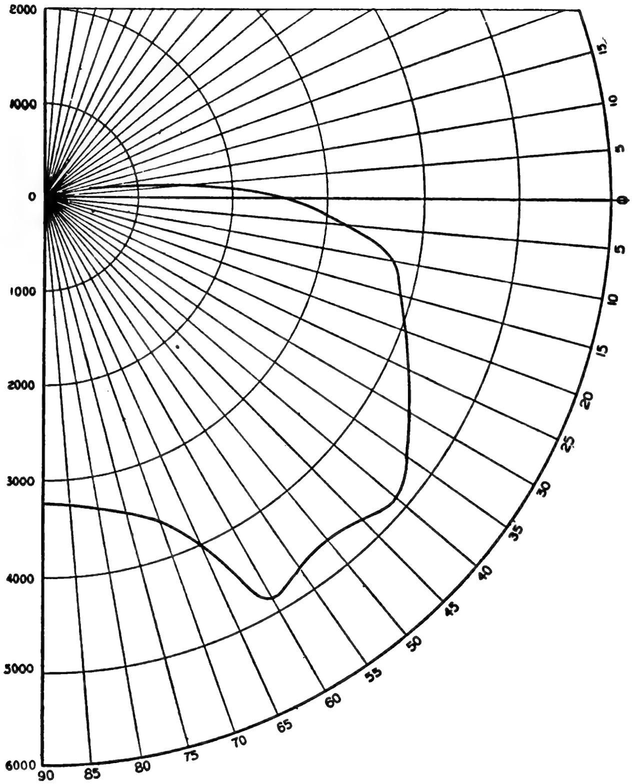


FIG. 22.—Distribution Curve for Crompton-Blondel 10-ampere Lamp. No Globe.

zine was refilled when necessary. The curves are really too favourable, as the lamp was burnt indoors and the globe did not get dirty on the outside. The test was run for 125 hours, after which a large amount of deposit from the economiser fell off and the candle-power increased considerably; the 150-hour test is not, however, given, as it is not likely that this automatic cleaning process will find favour with electrical engineers, and magazine lamps run until the globes are quite full of carbon ends. It would appear from this test that a life with one trim of more than about 50 to 75 hours would not be economical.

TABLE XIII.

Test Results of Blondel Carbons. Crompton-Blondel Lamp. No Globe.

Carbons: Positive, 14 mm. Blondel. Negative, 9 mm. cored, open type.

Figure.	Amperes.	Arc Volts.	Watts.	Total Consumption, mm. per Hour.	Mean Spherical.		Lower Hemispherical.	
					C.P.	W./C.P.	C.P.	W./C.P.
24*a*	10	37·5	375	38·1	1,165	0·322	2,240	0·167
24*b*	10	39·2	392	38·3	1,519	0·258	2,900	0·135
24*c*	10	39·4	394	42·2	1,525	0·258	2,890	0·136
24*d*	10	39·6	396	46·1	2,231	0·178	4,177	0·095

TABLE XIV.

Candle-power and Efficiency of Yellow Flame Arcs. Bare Arcs: Efficiency of Arc Alone.

Current and Lamp.	Mean Spherical.		Lower Hemispherical.	
	C.P.	W./C.P.	C.P.	W./C.P.
Inclined carbon, 6 amperes	740	0·36	1,370	0·19
Inclined carbon, 8 "	1,050	0·34	1,910	0·19
Inclined carbon, 10 "	1,520	0·29	2,920	0·15
Inclined carbon, 12 "	1,960	0·29	3,490	0·16
Regenerative, 5·5 "	780	0·46	960	0·37
Blondel, 10 "	1,400	0·28	2,680	0·15

Tests of Blondel Carbons.—A distribution curve for the Crompton-Blondel lamp has already been given, but in view of the fact that the Blondel carbons are a class apart, the curves in Fig. 24 and the test results in Table XIII. will be of special interest. All the tests were made in the same 10-ampere lamp, and show the results obtained with Blondel carbons of three different makes. For curves *a* and *b* the

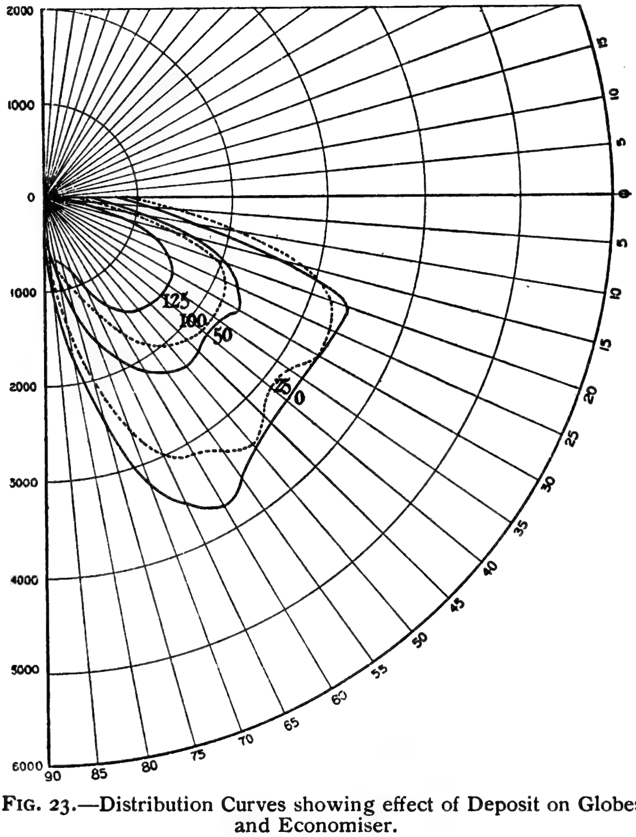


FIG. 23.—Distribution Curves showing effect of Deposit on Globes and Economiser.

carbons were from two foreign makers. For curves *c* and *d* the carbons were of the General Electric Company's make, those for test *c* containing approximately 50 per cent., and for test *d* approximately 60 per cent. of calcium fluoride in the core. The results from curve *a* are slightly inferior, but there is little to choose between those from curves *b* and *c*, except that the *b* carbons burn rather more slowly; the gain in efficiency with the *d* carbons should more than compensate for the quicker burning hours if it is not found possible to reduce these

without losing in efficiency. In steadiness of burning the order of merit was *d*, *c*, *b*, and *a*. These tests bring out a real superiority of the Blondel carbon when full advantage is taken of its possibilities, especially when the relatively slow rate of consumption as compared with standard flame carbons is taken into account.

Comparison of Tests.—Care must be taken not to draw too hasty conclusions by comparing the results obtained in different sets of tests. It

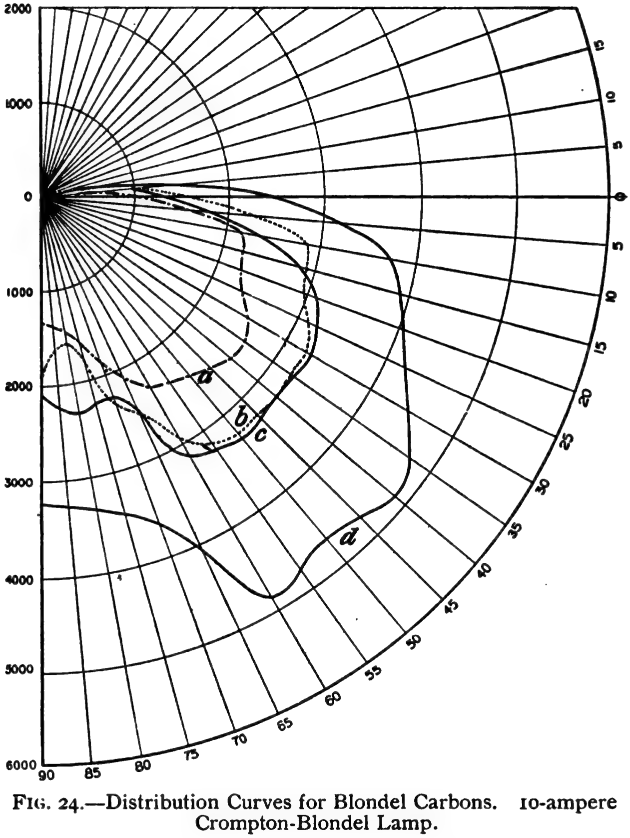


FIG. 24.—Distribution Curves for Blondel Carbons. 10-ampere Crompton-Blondel Lamp.

has been pointed out that variations exist between different batches of carbons of the same make, as between different makes; only a very large number of repeated tests would enable a very accurate average result to be reached. For example, if the test results for the 8-ampere Excello lamp in Tables VI. and VIII. be compared, it will be noticed that there is a fair difference in the figures obtained for candle-power and efficiency. Or again, if the figures for the Angold magazine lamp with

globes in Table VII. be compared with those for the same lamp without globes in Table X., it would seem that so far from the globes absorbing any light they have actually produced an increase in both light and efficiency. Both these discrepancies are easily understood when it is realised how slight differences in the carbons may vitiate such comparisons. As has already been pointed out, the greatest care was taken to eliminate such differences in any one set of tests, but the different sets were carried out at different times, in some cases as much as twelve months apart, and under such circumstances such variations were unavoidable.

In endeavouring, therefore, to arrive at an average figure for candle-power and efficiency of the yellow flame arc from these tests, the best method is perhaps to take the average of the results obtained (eliminating, of course, all tests not under standard conditions) and to round

TABLE XV.

Carbon Costs in Pence per 1,000 Candle-hours. Bare Arcs.

Current.	Metal-cored Carbons.		Plain Carbons.	
	Mean Spherical.	Lower Hemi-spherical.	Mean Spherical.	Lower Hemi-spherical.
6 amperes	0·244	0·132	0·170	0·092
8 "	0·196	0·108	0·137	0·075
10 "	0·150	0·078	0·105	0·055
12 "	0·131	0·073	0·092	0·052

the figures up. Though the author thinks that the figures thus reached may be regarded as representative, they should not be looked upon as absolute, nor does it seem possible that any really absolute figures could be given. If, however, this is done, we get the results in Table XIV.

Combining the figures in the first four lines of this table with the carbon costs per hour already calculated, we arrive at the carbon costs per 1,000 candle-hours given in Table XV.

It will be seen that the carbon costs are very low per 1,000 candle-hours, and if similar calculations are made for open type carbons they will be found to be almost exactly equal to the cost of metal-cored carbons. The outcry which was raised against the cost of flame carbons is therefore seen to be quite unjustified even for metal-cored carbons, and much more so in the case of plain carbons. The actual running costs are obtained by adding these carbon costs to the cost of

energy and trimming and depreciation allowances. The latter are so variable that there is no object in attempting to calculate them ; the former are obtained at once from the figures for watts per candle in Table XIV., which are numerically equal to the cost of energy in pence per 1,000 candle-hours when energy is supplied at 1d. per unit. Engineers will be able to make their own estimates according to circumstances, but whatever the conditions may be, no other electrical light source will be found a possible competitor of the yellow flame arc where large light units can be used.

Globes.—The majority of the results published apply to bare arcs, and, of course, in actual practice allowance must be made for loss in globes. Messrs. J. T. Morris and J. G. Farrow recently carried out some tests on flame lamp globes which were published in *The Illuminating Engineer* (vol i. p. 985), and which gave absorptions ranging from 15 to 32 per cent. The tests were carefully made by determining the distribution curve and then calculating the M.S.C.P. with and without globe. For reasons which will be clear from what has already been written, the author is inclined to distrust this method, and believes that the only satisfactory method would be to use a spherical photometer. It is eminently desirable that some really comprehensive tests on this subject should be made, and, if possible, some system of grading arc lamp globes according to their absorption devised, so that when buying either lamps or new globes one could be more or less certain that one was getting an article which did not destroy all the efforts after efficiency of the arc lamp and carbon-makers.

In conclusion, I must give my very best thanks to Mr. H. E. Crocker, who has supervised and carried out all the experimental work for this paper; also to Mr. A. J. Capener, who has assisted him throughout. When it is realised that the curves published alone involved some 15,000 photometer measurements, and that a large number of other curves have been actually taken and discarded for one reason or another in making the final selection, it will be seen that Mr. Crocker's and Mr. Capener's task has been no light one. Finally, I must thank the General Electric Company, in whose laboratory the work has been carried out, for permission to publish the results. I trust that on some future occasion I may be able to supplement this paper with figures for alternating and for white flame arcs.

Discussion.

Dr. W. E. Sumpner: I should like to inquire the reason why the copper core proved satisfactory in view of the fact that the copper coating did not. With reference to the images of flame arcs shown, I should be glad if the author would inform me whether any theory of the action of the calcium fluoride has been advanced to explain the different effect with the positive and negative carbons. Referring to the enormous amount of testing involved in the work of the paper, I would suggest that the mean spherical candle-power could be Dr. Sumpner.

Dr. Sumpner. obtained by one measurement by placing the source of light in a chamber with suitable reflecting walls and an orifice properly disposed. In connection with the question of absorption by globes, I might draw attention to the fact that owing to internal reflection more light is actually absorbed by the globe than would otherwise be the case.

Mr. Milnes. Mr. W. E. MILNES: The flame arc is the great weapon of electricity against high-pressure gas. It has, however, the following drawbacks: (1) Its first cost is much higher than that of the high-pressure gas lamp. (2) It is usually necessary to burn 4 or 5 in series to secure the greatest economy. (3) Although we are assured by the author that carbon makers and not lamp makers are responsible for the development and efficiency of flame lamps, the lamps become obsolete after two or three seasons' use. These drawbacks accounted for the growing use of high-pressure gas lamps. The paper draws attention to the importance of a careful selection of carbons. The curves given will prove of great use to engineers and users of lamps. It should, however, be emphasised that, while not underrating the question of quality in carbons, the question of quality in the lamp is important. All flame arcs have not satisfactory mechanism, nor is the mechanism always adequately protected. The user of the lamp does not always appreciate the importance of the type of globe carbon tray, dioptric or other inner globe or reflector. The paper will, however, undoubtedly lead to a more intelligent use of arc lamps, showing as it does the relative importance of the various factors which combine to give illumination. It is interesting to find that large users of arc lamps (works, railway companies, and others) are now rightly considering the value of polar curves. These consumers require scientific illumination, and each case should be carefully considered. Such consumers now appreciate the importance of height of lamp, distance apart, voltage across arc, current, type of reflectors and globes, and other points which determine even illumination. On the other hand, the small user—the shopkeeper who wants "light"—is usually hopeless. He hangs four 10- or 12-ampere flame lamps outside his window at a height of about 10 ft. above the pavement. Polar curves do not interest him. He should be given a weather-proof lamp, the mechanism of which is simple and as fool-proof as possible. Carbon-holders and globes on this lamp should be cheap, as he is likely to call for several during the year. The effect of carbons on candle-power cannot be made of interest to him. He buys one grade only—the very cheapest. On the question of costs of illumination from flame-arc lamps, the following figures obtained from a local flame-arc lamp experiment might be of interest. Ten 7-ampere magazine flame lamps, 5 in series on 220 volts, were being run in competition with 10 twin-mantle "Keith Blackman" high-pressure gas lamps. The approximate maximum candle-power from the arc lamps totalled 16,400, the current consumed for which amounted to 3·1 units per hour. The maximum candle-power obtained from the gas lamps totalled 6,600, the consumption being at the rate of 170 cub. ft. per

hour. Taking electricity at 2d. per unit and gas at 1s. 10d. per 1,000 cub. ft., this shows a cost of approximately 0·38d. per 1,000 c.p.-hours for flame arc lamps and 0·57d. per 1,000 c.p.-hours for high-pressure gas mantles. This comparison emphasises a most important point. The candle-power from flame arc lamps is practically constant, whereas the candle-power from high-pressure gas falls off rapidly and is affected to a very great extent if the mantle is torn or not properly hung. Fifty per cent. variation in candle-power can be accounted for by either of these causes. Dealing with the cost of maintenance, observation told us that the average life of a high-pressure gas mantle was 80 hours, while the arc lamps referred to burnt approximately 80 hours for one trim. The attendance charges were approximately the same. The cost of carbons per trim work out at 1s. when bought in quantities. The cost of mantles bought in quantities is the same. The maintenance charges are therefore the same, excluding the labour in lighting and turning off. High-pressure gas is never debited with the cost of low-pressure gas on the by-pass which amounts to approximately 0·3 cub. ft. per by-pass per hour. Actual tests prove that we need not fear the competition of high-pressure gas, but we should not allow our customers to be misled by the misstatements of candle-power usually given by the manufacturers of high-pressure gas lamps. Mr. Milnes.

Mr. A. T. Bartlett: The question of metal filament lamps as compared with arc lamps has been mentioned in the paper. I have been looking into the matter and find that the cost of high candle-power metal filament lamps per 1,000 c.p.-hours comes out roughly the same as that for carbons for flame arcs, the advantage being slightly in favour of the former. In arriving at this result the lower hemispherical candle-power was taken and an allowance of 25 per cent. due to loss in globes, also the working voltage of 50 volts per lamp was taken instead of the 44 across the arc. The only thing left to consider therefore was the watts per candle-power, and this worked out two or three times greater for the metal filament. Distribution of light must, however, be considered; 1 c.p. or 1 c.p. per foot is not always equally effective, and I would urge that the source of light should be concealed and that the disadvantage of metal filament lamps would be reduced in some cases by the adoption of a larger number of smaller units: any method of reducing the watts per candle-power would help along illumination with concealed source, and this raises the question of flame arcs suitable for the purpose. I am looking forward to the results promised with alternate-current arcs, and should like to ask for a rough figure of relative efficiency. I might point out that the economiser was used on Continental open arcs long before the advent of the flame arc. Mr. Bartlett.

Mr. A. E. Brewerton: The author has pointed out in one part of the paper that voltage variations would occur in the arc as the carbons burnt away were the resistance not decreased by coppering or by the use of an internal conductor. This is, of course, when contact is made at the top of the carbons, but there is an obvious remedy, which con- Mr. Brewerton.

Mr. Brewerton.

sists in placing an additional contact brush near the bottom ends. Such an arrangement is now very popular, and although this was referred to by the author briefly, I think he will join with me in advocating this as a satisfactory method of dispensing with the metal core and so reduce the carbon cost. In photometering converging-carbon flame arcs, the author explained that readings were first taken at right angles to the arc, but in the second set of readings he did not say whether the positive or negative carbon was nearer the photometer. I believe that very much higher readings can be obtained when the photometer is directed towards the arc crater, especially when a pure carbon negative is used, a fact which is very important in photometering street lamps. I cannot agree that the burning hours of the magazine lamps are necessarily restricted to 50 to 70 hours, although the curves show a decided diminution of light with one particular kind of lamp. That the amount of deposit depends upon the ventilation is, however, exemplified by the "deposit free" globes, and therefore tests taken on one lamp cannot be said to hold good for another. I understand that one maker of magazine lamps is placing a 120-hour lamp upon the market, and it would appear that his views upon the subject differ from those expressed in the paper. I think that standardisation of globes is a proposition deserving of consideration, and as the author represents a firm manufacturing arc lamps as well as carbons I should like to know whether they adopt any classification of globes according to their degree of opalescence. Of course it is not possible to adopt a single density, as it is well known that shopkeepers often prefer a globe which absorbs a large proportion of the light, since it then appears wholly incandescent from a distance, and this may be better for advertising purposes than an efficient illuminating medium. One arc lamp maker a few years ago placed upon the market a flame lamp which became very popular amongst shopkeepers, and I venture to think that its success was almost entirely due to the adoption of a very opaque globe. In designing any arc lamp globe where a dioptric is not employed, the starting-point should be to make it as nearly hemispherical as possible, with the arc at the centre. By this means the light passes directly through the globe and hence through a minimum amount of glass, refraction being eliminated and also much of the internal reflection mentioned by Dr. Sumpner. I think that with a globe of this kind the light lost must be very nearly in direct proportion to the absorption due to opalescence. Of course any arc lamp globe would increase in density as time went on, owing to the attack of hydro-fluoric acid, so that with any attempt to bring about the proper use of globes, it is not only necessary to see that the consumer buys the right grade, but that he discards the old ones when they become too dense. I fear, however, that advice of this kind will be looked upon with great scepticism by users, especially those who can hardly be induced to scrap globes which are badly broken.

Mr. Forster.

Mr. A. LINDSAY FORSTER: I should like to refer briefly to an enclosed long-burning arc with flame carbons which has recently come to my

notice. Both carbons are coreless, and are placed concentrically and vertical, the volts across the arc being about 100. The lamp is constructed with an annular cooling chamber of thin copper, the idea being that there is sufficient circulation to carry the vapour given off by the arc into the cooling chamber where the fluorides will be deposited. I noticed that while the lamp was burning there was an appreciable fog in the globe, which suggested that we had not only to consider the shape of the globe but also the size, since it would be important as determining the amount of fog the arc has to penetrate. I should be glad if the author would kindly give some information as to the effect of the fog in this connection. **Mr. Forster.**

Mr. Solomon. Mr. SOLOMON (*in reply*): As regards Dr. Sumpner's question about the theoretical explanation of the different behaviour of the calcium fluoride in the positive and negative carbons, I may say that we have made a number of experiments on that point, but have failed to arrive at a definite conclusion as yet. With regard to the difference between coppered and metal-cored carbons, it is pointed out in the paper that the copper coating did not burn away evenly, and this was no doubt partly due to the oxidation which the copper undergoes on the outside of the carbon; in addition, it is obvious that the copper could not melt without the risk of some of it coming into the arc, which risk was lessened by the use of metal-cored carbons. With reference to the amount of labour involved in obtaining distribution curves as compared with determining the mean spherical candle-power in the way suggested by Dr. Sumpner, I should like to point out that the distribution curves are now very largely used and asked for by engineers, and therefore this labour is not wasted, although for many purposes the spherical photometer will give all the information required. I should like to ask Dr. Sumpner whether a cubical room was theoretically as accurate as a spherical one? [Dr. SUMPNER: I believe that is so.] As regards globes, Dr. Sumpner is correct in saying that the internal reflection increases the absorption, but of course if the candle-power is first measured with and then without the globe, the actual amount of light lost could be determined. Such measurements can, in my opinion, only be made satisfactorily with a spherical photometer which would enable the two determinations to be made quickly one after the other.

Mr. Milnes' remarks do not call for any reply from me, but I should like to thank him for the figures comparing flame lamps with high-pressure gas, and would merely point out that the comparison, being made on the basis of maximum candle-power, seems to lose some of its value.

I agree with Mr. Bartlett that in the question of comparative costs of flame lamps and metal filament lamps, the cost of carbons is approximately the same as the cost of renewals of lamps. Comparing in each case an installation of 1,000 mean spherical candle-power, allowing for absorption by globes and for 50 volts per lamp in the case of the arc lamps, I find that the cost per year (4,000 burning hours) for carbons and depreciation comes to £4 10s., and for new metal filament

Mr. Solomon.

lamps and depreciation of fittings comes to £3 16s. As regards trimming and attendance costs, these may be estimated at £2 for the arc lamps and 10s. for the metal filament lamps. These two items leave a balance of £2 4s. per year in favour of the metal filaments. Against this the cost of current at 1d. per unit will be slightly under £7 for the arc lamps and slightly over £18 for the metal filament lamps, leaving a balance of about £10 in favour of the arc lamps. It will thus be seen that the cost of using metal filament lamps for street lighting where 1,000 c.p may be required is much greater than when using yellow-flame arc lamps, the difference amounting to about £10 per post per annum. The comparison is still less favourable to metal filament lamps if it is made on the basis of lower hemispherical instead of mean spherical candle-power, as the metal filament lamp will lose considerably by the use of a reflector. Where much smaller light units are required metal filament lamps may be satisfactory, but it will be found in most cases that arc lamps can be installed for the same maintenance cost and giving better illumination.

In reply to Mr. Brewerton, I have referred in the paper to the fact that the method of making contact to the bottom of the carbon has apparently not been found satisfactory by the arc lamp makers, as it was being more or less generally discarded. With regard to the variation in light when photometering towards the positive or negative carbon, the figures given in the paper average these two measurements because of the use of two mirrors. For general purposes the arc must be looked on as a nearly symmetrical light source. I am aware that magazine lamp makers are increasing the burning hours obtained with one trim, but am of opinion that it is an unwise policy, and the actual measurements given in the paper support this view. It is true that ventilation in modern flame lamps is so good that the globe keeps very clean, but there is no doubt that the economiser becomes considerably choked.

In reply to Mr. Lindsay Forster, the lamp he describes is similar to the Jandus arc lamp, a test result of which is given in the paper.

POWER GENERATION AND DISTRIBUTION IN THE CLYDE VALLEY ELECTRICAL POWER COMPANY'S AREA.

By DAVID A. STARR, Member.

(*Paper received 24th April, and read before the* SCOTTISH LOCAL SECTION *13th May*, 1912.)

In the following paper, which the author has been asked to contribute to the Scottish Local Section of the Institution, an endeavour is made to outline the early history, the equipment, and the system of distribution; also to give a general idea of the progress of a company on which a great many of the largest industries in the west of Scotland are depending for their motive power.

Some eighteen years ago the Clyde Valley scheme was first discussed by the members of the firm of Messrs. Strain and Robertson, consulting engineers, Glasgow. The idea at that time was to apply for a provisional order and to obtain the authority of Parliament to erect a power house at or near Motherwell, on a site to be located at one or other of the numerous collieries in the vicinity where fuel could be delivered cheaply from the pit mouth. Their intention was to distribute and sell electrical energy for all purposes in Motherwell and vicinity, and possibly to serve an area within a radius of 8 to 10 miles.

Their plans were somewhat hampered by the restrictions imposed by the Board of Trade at that time on the distribution of electricity, and the whole scheme was allowed to remain in abeyance until the Electric Lighting (Clauses) Act of 1899 was passed. This Act considerably facilitated the development of electrical enterprise in Great Britain, removing as it did many of the objectionable restrictions which had previously prevented electrical development on any large scale.

In the following year (1900) the matter was taken up more vigorously, and a number of capitalists in and about Glasgow became interested in the promotion of the company. The late Sir David Richmond, who had just retired from the Lord Provostship of Glasgow, became interested in the scheme, and was the company's first chairman. He had as colleagues James Mackenzie, LL.D. (the present chairman), the late Lord Hamilton of Dalzell, the late Sir William George Pearce, Bart., Sir Mitchell Thomson, Bart., Sir Charles Cayzer, Bart., the late Dr. Francis Elgar, Colonel C. M. King, Mr. Fred Lobnitz, and several others.

A much larger scheme than had at first been considered was then decided on, and a bill was promoted and Parliamentary powers applied for in 1900, in which authority was asked to generate and distribute electrical energy over an area comprising some 750 square miles. At that time there was only one company in Great Britain distributing power for commercial purposes over any such large area, viz., the Newcastle-upon-Tyne Electricity Supply Company, Ltd.

After a syndicate had been formed to guarantee the preliminary expenses, and application had been made to Parliament, it was discovered that strenuous opposition in the form of a rival company had developed under the name of the Caledonian Electric Power Company. This company applied for similar powers, embracing, however, a much larger area than was covered by the Clyde Valley Electrical Power Company's Act, extending to Ayrshire, and taking in the coal-fields and larger industries there.

In August, 1901, royal assent was given to the Clyde Valley Electrical Power Act (1901). Besides the general powers conferred authority was given to construct three generating stations, and to lay cables and distribute power in twenty-six parishes in the county of Lanark, sixteen parishes in the county of Renfrew, six parishes in the county of Dumbarton, and three in the county of Stirling, an area of 750 square miles in all, excluding the city of Glasgow, the burghs of Partick, Govan, and Paisley, and other burghs within the boundaries of the company's area, where local plants were already established or provisional orders had been granted.

Early in 1902 negotiations were opened with manufacturing companies and contractors for the purchase of plant and apparatus, erection of buildings, etc., and in the summer of the same year a contract was entered into between the Clyde Valley Electrical Power Company and the British Westinghouse Electrical Manufacturing Company, Ltd. This contract covered the erection of buildings, the first installation of generating plant, both steam and electrical, the laying of a certain amount of cables, the erection of overhead wires, and the construction of several sub-stations.

The system of generation and distribution decided upon was 3-phase alternating current at a pressure of 10,000 to 11,000 volts between phases, and a periodicity of 25 cycles per second.

It was decided to erect two power stations, and sites were procured —one at Yoker, on the Clyde, opposite Renfrew, and the other near Motherwell. Construction work was commenced on the buildings during 1902, and in August, 1905, the Yoker power house and generating plant was handed over to the company. In December of the same year the Motherwell power house was completed and taken over, as were also a certain amount of main cables and several sub-stations. The power house buildings were very similar in design, and the plants identical in each, excepting the system of condensing.

It was primarily intended to install reciprocating engines in large units, but in view of the rapid progress which had been made in

the development of the steam turbine, and the higher efficiency obtainable from this type of prime mover, it was ultimately decided to install turbines.

At the time the plant was handed over to the company the following had been installed in each power house : 4 Babcock and Wilcox water-tube boilers, land type, each having a guaranteed evaporation of 16,000 lbs. per hour, 88·3 sq. ft. of grate area, and 4,400 sq. ft. of heating surface. These were equipped with superheaters, 750 sq. ft. heating surface, and economisers and feed water pumps were installed.

The boilers in both power houses were equipped with Roney (American) stokers, each pair of stokers being driven by an independent 4-H.P. steam engine. Flues were constructed and stacks erected, the latter being on the Custodis system, having an internal top diameter of 11 ft. and 225 ft. in height from the top of the foundations.

The boiler houses were constructed large enough to accommodate double the boiler plant originally installed, and coal conveyors and ash-handling plant were installed of sufficient capacity and dimensions to serve the ultimate output of the boiler houses. The framework of the coal bunkers, which were overhead, was completed the full length of the building, but the concrete bunkers were only completed for the boilers then installed.

In the engine-room foundations were constructed for four generating units—two of 2,000 k.w. and two of 5,000 k.w. One end of each building was used for offices, switchboard galleries, main and selector switches, cubicles, busbar chambers, etc. This part of the building has three floors besides the basement. The control switchgear, instruments, and busbars, are erected on the top floor, giving the operators in charge of the switching arrangement a full view of the turbines, generators, and other plant in the engine-room. The other floors are used for selector switches, cubicles, and the power house transformers, etc.

Two turbo-generators with relative condensing plant were installed in each power-house ; these had a nominal capacity of 2,000 k.w. each.

The turbines are of the Westinghouse Parsons double-flow type direct connected to generators of a similar capacity generating 10,000 to 11,000 volts, 3-phase, 25-period current. The generators are separately excited and two 75-k.w. direct-coupled exciters, 125 volts were installed. One of these is used as a spare. The main and selector E.H.T. switches, as well as some of the auxiliaries, such as coal conveyors and hot well pumps, were formerly operated by current from these exciters, which were direct connected to independent steam engines of Westinghouse compound type with Worthington condensers.

The main condensing plant (owing to physical conditions) was different in each power house. At Yoker surface condensers were used, whilst at Motherwell the condensing was done on the barometric jet principle.

At Yoker where the power house is located on the banks of the

Clyde, and where there was a short lift of water, the condensing plant consisted of a Mirrlees Watson vertical surface condenser and a dry air pump for each unit. Suction and discharge pipes of 36 in. diameter were laid between the condensers and a well close to the banks of the Clyde. Pipes of 30 in. diameter with controlling valves were laid in duplicate between the well and the river below low-water level. Circulating pumps were placed at the head of the pipe line next to each condenser. These were of the vertical centrifugal type directly connected to high-speed non-condensing steam engines.

At Motherwell, where the power house was located at an elevation of some 150 ft. above the level of the Clyde, a pump house was erected near the bank of the river, and a barometric jet condenser was erected at the power house. An exhaust pipe common to both generating units led into this condenser, so that the two turbines exhausted into one main exhaust pipe. This condenser was estimated to be large enough to handle two additional units of 2,000 k.w. each.

An 8-in. pipe line led from the pump house at the river to a cooling tower, which latter was erected close to the power house. The pipe line was 1,500 ft. in length with a rise of 150 ft. The pumps were of the three-throw plunger type, motor driven, their starting and stopping being controlled from the switchboard in the power house. An extension to the main buildings contained the pumping plant for the condensers, and two Alberger 2-stage dry air pumps were installed, together with two hot water and two cold water circulating pumps, these being all steam driven by independent non-condensing engines.

The foregoing is a general description of the generating plant as it was turned over to the Clyde Valley Company by the contractors in 1905. Since that time several additions and alterations have been made to the general equipment with the intention of meeting the increased demands for supply, and with a view of modernising the plant as much as possible, and particularly to accomplish more economical and efficient operation. First it was discovered that the Roney stokers, whilst having a very good reputation in America, with the general class of fuel used there, were unsuited for Scotch coal. These were replaced by chain grate stokers. The steam engines driving the Roney stokers were scrapped and electric motors were substituted. This work had to be done gradually, and the change-over has been justified by the large saving which afterwards took place in the coal consumption. It was next realised that the condensing plant at Yoker could be made much more efficient, and the steam-driven circulating pumps were replaced by motor-driven pumps placed in the well at the river instead of at the head of the pipe line next the condensers. This work soon justified itself by a further reduction in the fuel consumption. It was also found, owing to the fluctuating load and the small amount of power which was used during the night and over week-ends, that it would be advisable to install a smaller generating unit in each power house to handle these small loads. Accordingly a turbo-generator of 600-k.w. capacity

was installed at Yoker and one of 1,000 k.w. at Motherwell. Next, it was found that the day load was increasing beyond the capacity of any one of the generators, and having realised in practical operation that the turbines were of a much greater capacity than their nominal rating, it was decided to increase the capacity of the generators in proportion. The British Westinghouse Company undertook to rewind the generators on site and increase their output by 50 per cent., and this work was satisfactorily carried out. Additional by-pass valves were placed on the turbines, and the whole work was carried out without any interruption to supply. This gave at the beginning of the year 1910 a generating plant capacity in Yoker of 6,600 k.w. and 7,000 k.w. at Motherwell. Four additional boilers of a similar size to those first installed had been erected in Motherwell and also a second cooling tower. At this period the maximum load on feeders at Yoker was 2,500 k.w. and at Motherwell 4,500 k.w. The total connections of consumers' plant to mains aggregated 26,000 H.P.

At the end of 1909 a new line of underground cable was laid between Rutherglen and Renfrew, which connected the Yoker and Motherwell networks together, and in the beginning of 1910 this interconnecting cable was put in commission and enabled the plants in both power houses to be run in parallel. This immediately effected a decided saving, as during periods of light load the supply could be given from either one or other of the power houses. It also had other advantages, as current could be transferred from one area to another when and as required, and the loads could be so adjusted as to keep the plants in both power houses running at their best efficiency. Previous to the interconnecting of the power houses, when it became necessary to clean out flues, arrangements had to be made with the customers in the particular area for a complete shut-down for several hours, and although the time chosen was usually a Sunday during the new year or fair holidays, when almost all the works were shut down, still it had many drawbacks, and some smaller customers were more or less inconvenienced. The linking up of the power houses permitted of such work being done at any time.

Early in 1910 it became necessary to increase the generating plant at Motherwell, and an order was placed with the British Westinghouse Electric and Manufacturing Company, Ltd., for a 5,000-k.w. turbo-generator of the Rateau type, the manufacturers agreeing to take in part payment the 1,000-k.w. turbo-generator, as there was now no necessity for the smaller unit. This 5,000-k.w. set was installed during the autumn of 1910, and put in commission at the end of that year. On test the steam consumption indicated on the average day's load at least 25 per cent. less than the consumption of the turbines originally installed. The turbine was constructed on the Rateau system, with a Curtis ring for the high-pressure impulse end. The generator embodied all the latest improvements in modern power plant design. The field is energised from an exciter directly coupled on the end of the main shaft. The

windings are kept cool by means of an external electrically driven fan. The end windings are specially braced to resist displacements arising from short circuits. The overload capacity is 25 per cent. for 6 hours and 50 per cent. for 10 minutes. A series of exhaustive tests were taken on site, when it was found that the makers' guarantees were fully met, as shown by the following results, which are corrected to 175 lbs. steam pressure, 150° F. superheat, and 28½ in. vacuum.

Per cent. load	125	100	75	50	25
Steam consumption :—					
(Lbs. per kilowatt-hour.)					
Guaranteed... ...	15·00	15·00	15·2	17·5	21·6
Actual	13·45	13·35	13·6	14·5	17·8

Owing to the necessity of maintaining 125-volt direct-current supply, which was mainly used for exciting purposes for the old sets, as well as the operation of switches and auxiliary motors, it was decided to have the field of the exciter on this generator separately excited with 125 volts. This ensured better regulation, especially in the event of any slowing down of the generator, due to temporary short circuits. The field circuits are also so arranged as to be self-excited if necessary.

Two new boilers were installed of the Babcock and Wilcox water tube type, but of larger capacity than those originally installed. These boilers, each giving an evaporation of 33,000 lbs. of steam per hour, have a grate surface of 144 sq. ft., 7,322 ft. heating surface, and 1,435 sq. ft. heating surface in superheaters. The flues and economisers were placed behind the boilers; a steel stack was erected common to both boilers, also an exhaust draught system with motor-driven fan. Special chain grate stokers suitable for handling the lower grades of fuel are used, and the boilers are guaranteed to give their contract evaporation with the energy absorbed by the mechanical draft not exceeding 30 B.H.P.

In the original design of the power house it was intended, after the first boiler house was full, to extend the boiler house adjoining the main building, and install additional boilers, flues, economisers, as well as erecting a new stack. On looking into the question, however, it was found that the present coal bunkers, which have a capacity of 1,200 tons, and the conveying plant, would also have to be extended, and it was decided that these boilers, as well as two similar additional sets, could be placed in a building directly opposite the first set of boilers, and in a position where the same bunkers and conveyors could serve the new units. This also brought the boilers nearer to the turbines, and effected quite a large saving in the original estimate for boiler extensions.

The condensing system, due to the poor vacuum obtainable with long lengths of exhaust piping, and the high temperature of water from the cooling towers, next received very careful consideration by the engineers and management, and it was decided to install a system of surface condensing for the new plant. The distance between the power house and the river Clyde, also the difference of levels between

the power house and the river, presented many obstacles. Wayleaves had to be secured for the pipe line over an entirely different route than that of the pipe which supplied the cooling towers, and a new pump house and pumping equipment had to be designed. Contracts were eventually entered into with Messrs. G. and J. Weir, Ltd., Glasgow, for all machinery connected with the new condenser plant. Consideration was given to the steadily increasing output of the power house, and it was decided to construct a pipe line of sufficient capacity to supply condensing water for four 5,000-k.w. sets or their equivalent. The condenser is of the Weir uniflux type, having a capacity of 80,000 lbs. of steam per hour with 7,000 gallons of water per minute and a cooling surface of 6,000 sq. ft. The air pump in the power house is of the Weir dual motor-driven type, and two pumping units have been placed in the pump house at the river. These latter consist each of an Allen rotary circulating pump direct coupled to a 3-phase 400-volt 25-period motor, having a nominal output of 350 H.P., but with a guaranteed overload of 100 per cent. for 6 hours. It was found that 650 H.P. was required to drive each of these pumps and supply sufficient water for the condenser, and advantage is taken of the difference in levels already indicated to obtain a certain amount of power from the head of return water. A water turbine is direct coupled to the other end of the pump shaft and the main motor, circulating pump, and water turbine, are erected on one common bedplate. The pipe line is first filled by the motor on its overload, and as soon as there is sufficient head in the return pipe the valves of the water turbine are opened gradually, when the full volume of return water is flowing. A saving of over 40 per cent. is effected in the power required to operate the circulating pumps. In practice it has been found that these pumping units are capable of doing more work than originally specified—viz., to supply one condenser for a 5,000-k.w. set on overload. It has been found quite practicable to operate the condensers for two turbo-generators of 5,000 k.w. each at or near full load, with one of these pumping sets. The pipe line can be filled and the water turbine put in operation within 20 minutes of starting up. To give some idea of the economies effected here, it may be mentioned that in daily operation under the old system of barometric condensing, using water towers for cooling, there were running continuously, in addition to the pump for the make-up water at the river, four circulating pumps, two for hot water and two for cold water, the pumps aggregating 225 H.P. These pumps were steam-driven by direct-current high-speed engines and were taking approximately 75 lbs. of steam per horse-power. By shutting these down and utilising the new plant 100 to 125 H.P. more was used, but this is electrically driven and does not take more than the equivalent of 15 lbs. of steam per kilowatt-hour. The results actually obtained with the new turbo-generator and the pumping and condensing plant have shown a saving of 30 per cent. in the fuel consumption at the Motherwell power house. The air pump at the power house, which is motor driven, takes only 12½ H.P. when the turbine is

running full or on overload, and no trouble is experienced in maintaining a vacuum of from 96 to 96½ per cent. of the barometer.

The first 5,000-k.w. set with the condensing plant was put on commercial load in January, 1911. As the demands on the power house were still increasing, a second 5,000-k.w. set with similar condensing plant and to the same specification, was ordered and installed before the end of 1911.

The construction of the Motherwell pump house at the Clyde is worthy of mention. When this was being designed there was a possibility of future subsidence through mineral workings, and this had to be guarded against. Excavations were made, partly through rock, and a solid foundation large enough for the ultimate size of the buildings was constructed of reinforced concrete, 4 × 4 steel angles firmly bolted together were laid crossways about 18 in. from the bottom of the foundations. Another layer of similar angles was placed about the same distance below the level of the pump house floor, the whole being embedded in concrete. A sectional elevation of the arrangement is shown in Fig. 1.

The water-circulating pipes, both intake and discharge, were laid in the concrete and connected to the pumps and water turbines, so that in the event of any earth movement taking place, the whole foundation, building, and plant will move in one solid mass. The pipe line is constructed of riveted steel piping 42 in. internal diameter both for intake and discharge legs. These pipes rest on brick and concrete piers and the line for the most part is placed above ground. It was necessary, however, to cross two roads and two lines of railway. At these points the pipe line is underground, but both pipes are embedded in concrete; these form anchors for the line and occur at such convenient intervals that no damage is likely to take place from subsidence or from expansion or contraction. The intake at the river was first provided with grid screens as well as woven wire screens, but trouble was experienced by reason of leaves, twigs, branches, and other material coming down the river when in flood. A removable screen composed of perforated boiler plate was placed in the intake, and scrapers attached to a sprocket chain and driven by a motor have proved effectual in keeping the water clear of foreign material.

At Yoker a new 5,000-k.w. set is now being installed, the good results obtained from the operation of the Motherwell plant having decided the company to install similar generators and condensing plant there. The installation of a 10,000-k.w. unit is now being considered for the next extension to the Motherwell power house. In a short time the available generating plant at both power houses will consist of the following:—

Motherwell, four units:—

Two of	5,000	k.w.
Two of	3,000	„
Total	16,000	„

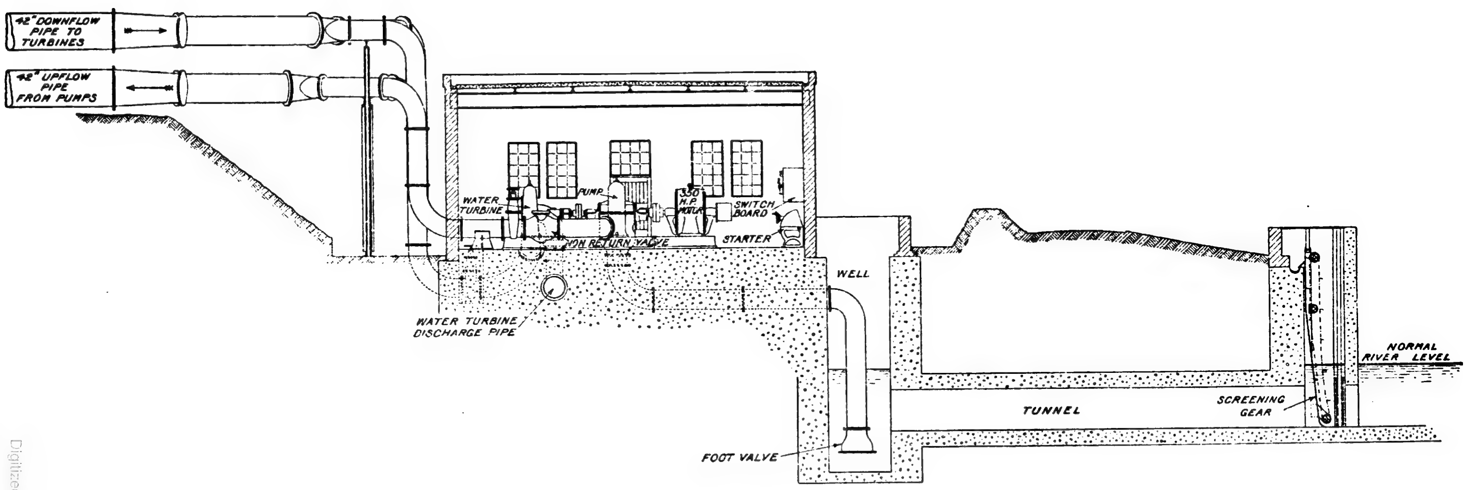

42" DOWNFLOW PIPE TO TURBINES
42" UPFLOW PIPE FROM PUMPS
WATER TURBINE
PUMP
350 H.P. MOTOR
SWITCH BOARD
STARTER
NON RETURN VALVE
WATER TURBINE DISCHARGE PIPE
WELL
FOOT VALVE
TUNNEL
SCREENING GEAR
NORMAL RIVER LEVEL

FIG. I.

The two smaller machines are at present kept as reserves in case of an accident to either of the other two sets.

At Yoker there will be three units :—

One of	5,000	k.w.
Two of	3,000	„
Total	11,000	„

For the present the two 3,000 k.w. will be kept as a reserve for the 5,000-k.w. set.

The boiler capacity at present at Yoker is 6 boilers, each having an evaporation of 16,000 lbs. per hour, and at Motherwell 8 boilers each having an evaporation of 16,000, and two having an evaporation of 33,000 lbs.

As previously mentioned, the first generators that were installed were separately excited and the exciters driven by independent steam engines directly coupled to 75-k.w. exciters. These were in duplicate in each power house, and until the beginning of this year it had been necessary to keep one of these sets running at each power house day and night. It is difficult to estimate the steam consumption of those sets, but it was known that this was very large and that a great deal of fuel was being consumed to keep them running. A storage battery has now been installed in each power house and a motor-driven exciter. These take the place of the steam-driven sets, which are only kept in case of accident. Each battery consists of sixty Tudor accumulator cells of 400-ampere hours' capacity, these are connected in series with a reversible booster.

Fig. 2 shows the authorised area and the present E.H.T. distribution, also the location of the power houses and sub-stations. At the present time there are upwards of 96 route miles of underground cable, and 21 miles of overhead lines, all operating at 11,000 volts, with 84 sub-stations and 6 switch houses. The company have acquired leaseholds and feus, and for their own distribution purposes have erected 14 of these sub-stations and switch houses, the remainder having been erected at the expense of the consumers, the company supplying the equipment only. All the E.H.T. distribution is at a frequency of 25 cycles and almost all the low-tension distribution is at the same frequency, the only exception being the Burgh of Clydebank, where lighting and small powers are distributed at 50 cycles. The reason of this departure from the standard is somewhat interesting. The Clydebank Electric Lighting Order (1901) was transferred to and taken over by the company, and at the time of the transference the Burgh stipulated that the supply was to be in the form of direct current. Realising, however, that this would necessitate a rotary converter at Clydebank, with its consequent attendance and other charges, the management effected a compromise with the Burgh authorities by agreeing to give the supply in the form of alternating current at 50 cycles, 25 cycle distribution for lighting being then in its experimental stage. This was

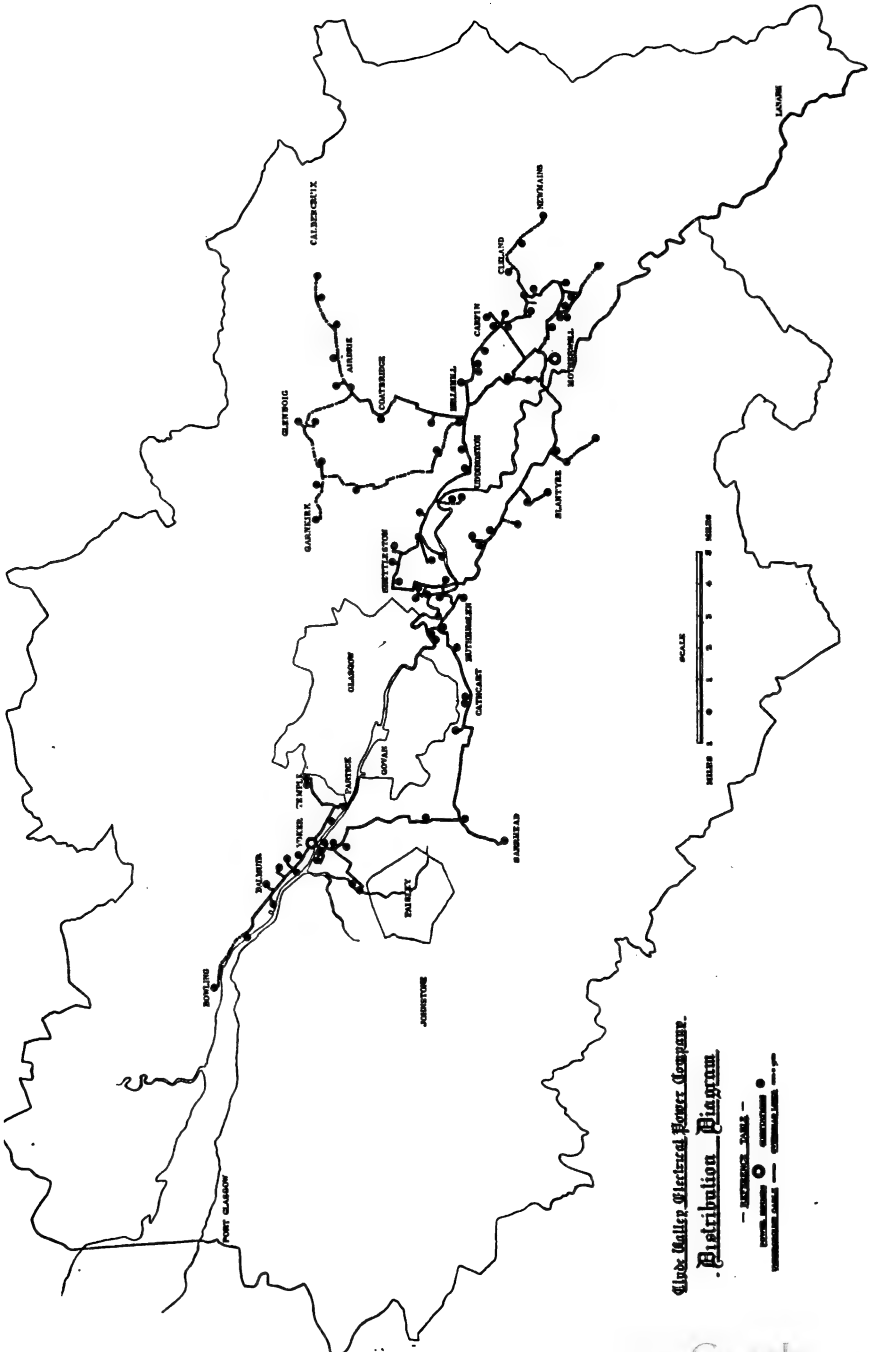

LANARK
NEWMAINS
CLELAND
CALDERCRUIX
CARFIN
MOTHERWELL
AIRDRIE
COATBRIDGE
BELLSHILL
GLENBOIG
UDDINGSTON
BLANTYRE
GARNKIRK
SHETTLESTON
RUTHERGLEN
GLASGOW
CATHCART
GOVAN
PARTICK
TEMPLE
YOKER
DALMUIR
BARRHEAD
PAISLEY
BOWLING
JOHNSTONE
PORT GLASGOW
SCALE
Clyde Valley Electrical Power Company.
Distribution Diagram.
— Reference Table —

FIG. 2.

accomplished by installing phase-changing plant in the Yoker power house. This plant consists of two units of 150 k.w., each composed of one 11000-volt 25-period synchronous motor direct coupled to a 3,000-volt 50-period generator. Main feeders carry the 3,000-volt 50-period current to Clydebank and Dalmuir, where it is transformed through street transformers to 400-volt 3-phase and 230 volts between phase and neutral. The phase-changing plant, being placed in the power station, requires no attendance other than can be given by the station staff.

The main E.H.T. network is laid out on the ring main system. The longest ring is upwards of 30 miles in route length and embraces Motherwell, Hamilton, Blantyre, Cambuslang, Rutherglen, Tollcross, Shettleston, Uddingston, Bellshill, and Carfin. The main cables in the neighbourhood of the power stations are lead covered and are drawn into 4- or 8-way stoneware conduits so that spare ducts are available for future extensions. The reason for this is to permit of the sectional area of conductors being increased in proportion to the load, and without having to make excavations each time a reinforcing feeder is laid. On other sections further removed from the generating stations the cables are laid in earthenware troughs. Stamped steel bridge-pieces held the cable in position in the trough, the trough being then filled up with bitumen, and the whole protected with a hard burnt tile 2 in. thick. This method of laying, while it probably gives the greatest security from electrolysis or acids, was found to involve rather too much capital outlay, particularly in outlying districts, where the cartage and transport charges on the various materials amounted to quite a large sum. During the past two years armoured cable laid direct in the ground has been used with success and economy. It has been found that this work can be carried out more rapidly as the men who on solid work would be engaged pitching and troughing are now fully employed excavating or filling in. Another point in favour of this system is the comparative freedom from accidents to the workmen employed. Former scalding accidents with hot pitch were of very frequent occurrence. The conductors in cables used in the E.H.T. main circuits are 3-core 0·15 sq. in., constructed for operation with generators having an earthed star-point. Paper insulation is used throughout. On some of the less important sections 0·1 sq. in. conductor is used, and on some branch lines for smaller power supply 0·035 sq. in. is the standard practice. Another feature of the distribution is the use of 11,000-volt street-disconnecting boxes. These are employed in cases of smaller power supplies, where the revenue to be derived from the load is not sufficient to justify the expense of looping in the main ring cables or the cost of erecting a switch house. These boxes are of special design, the distinctive feature being that each phase is brought into a separate porcelain cell to permit of the disconnecting link being oil immersed. Some of these have been in use for four years and have given satisfactory service. The company also have a considerable amount of extra high-tension overhead transmission. Such lines are employed in sparsely populated districts.

These serve a very useful purpose in development work ; isolated works are thus secured as customers which otherwise would have to be passed over on account of the revenue not being sufficient to meet the heavy cost of underground mains. The design of these lines has frequently been amended to meet extraordinary conditions, and to remedy defects which from time to time developed in practical operation. On some lines the trouble experienced from birds was of a most serious nature, earths and short circuits being of frequent occurrence, and in consequence the development of overhead construction was arrested until an efficient remedy was found. The bird trouble was confined principally to terminal poles or poles where shackle insulators are used, and the difficulties were finally surmounted by placing three shackle insulators tandemwise.

The general design of pole is as shown in Fig. 3, which represents a creosoted A pole having malleable cast bracket arms. The main conductors are set 30 in. apart, with the telephone and relay conductors carried underneath. The insulators are of the two-part design. Single-part insulators were first tried, but had to be discarded on account of unequal expansion and contraction during hot weather.

Where it was necessary to cross highways with E.H.T. lines a pole was erected on each side of the road, and the wires were protected by an earthed cage in accordance with the model description of the Board of Trade then in force. Although these cages were of ample size, and made of the strongest possible material, much trouble was experienced during heavy wind-storms by the cages swinging and making contact with the conductors. Within the last year, however, the Board of Trade have been induced to alter their specification, and now a double conductor is strung across the highways on separate insulators close together, and the two conductors are firmly clamped together at intervals of about 3 to 4 ft., so that in the event of a conductor breaking the strain is taken up by the remaining one. This system of road-crossing has now been adopted by the company, and the cages are being gradually replaced.

The protective system used is that generally known as the Merz-Price balanced protective gear. The pilot wires required for these are laid alongside the main cables in the case of underground work, whilst for overhead work they are carried as separate conductors on the pole line. The relays used are adjusted to operate on a fault current of 60 amperes, and by this means an ample margin of safety is left to allow of one or two branches being tapped off each protected section. Originally each section of overhead line was provided with lightning arresters at points where the overhead line joins underground cables. It was found, however, that these arresters disturbed the balanced protective gear whenever the atmosphere became electrically charged. Trouble from this source became so acute that it was decided to discard the use of these and depend entirely upon the lightning arresters installed on the sub-station busbars. Although there have been many severe thunderstorms since this change was made there has been complete immunity from

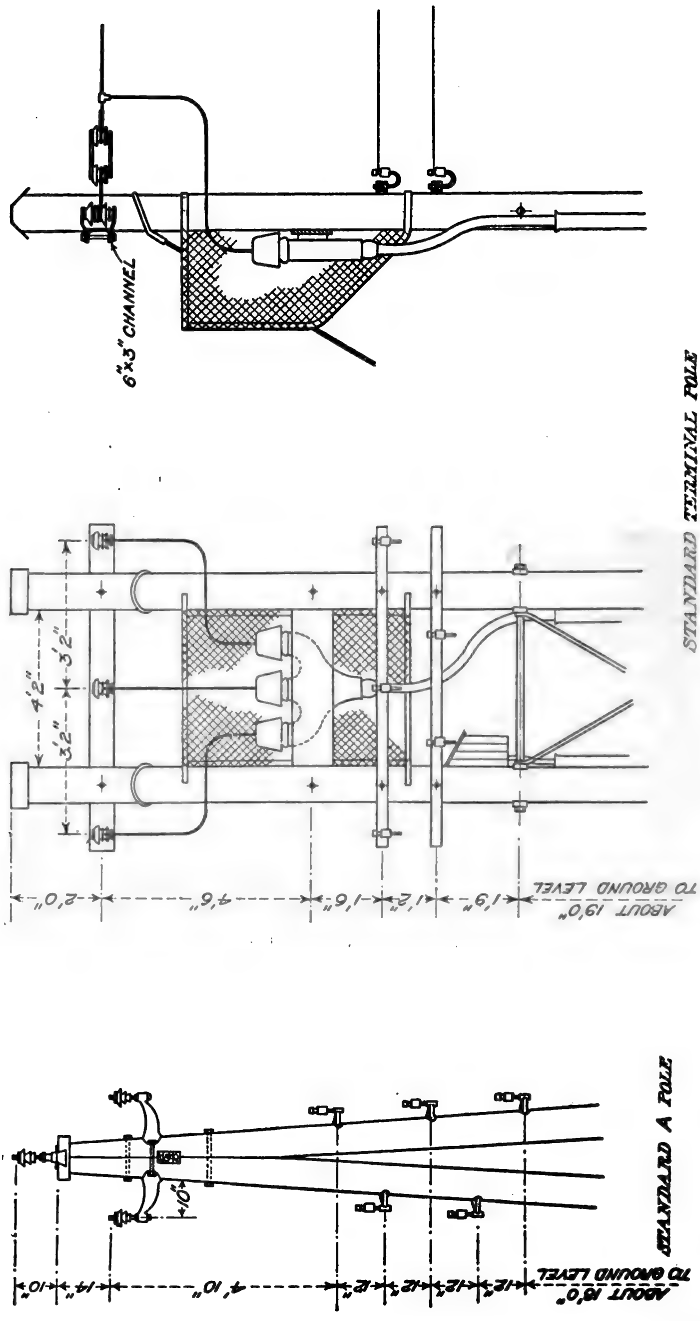

6"×3" CHANNEL
STANDARD TERMINAL POLE
4'2"
3'2"
3'2"
2'0"
4'6"
1'6"
1'2"
1'9"
ABOUT 19'0" TO GROUND LEVEL
STANDARD A POLE
10"
10"
14"
4'10"
12"
12"
12"
12"
ABOUT 18'0" TO GROUND LEVEL

FIG. 3.

accident or interruption. The sub-station equipments as now installed are the result of a gradual process of evolution. All the original sub-stations had 4 single-phase transforming units, one of these being kept as a spare. Gradually 3-phase transformers were used, and latterly when it was found from experience that these were absolutely dependable even under the most severe conditions, their installation has become standard practice. All the transformers are oil-cooled, and are wound for operating on primary 10,000- to 11,000-volt circuits mesh-connected and with tappings so arranged as to give a pressure of between 400 to 440

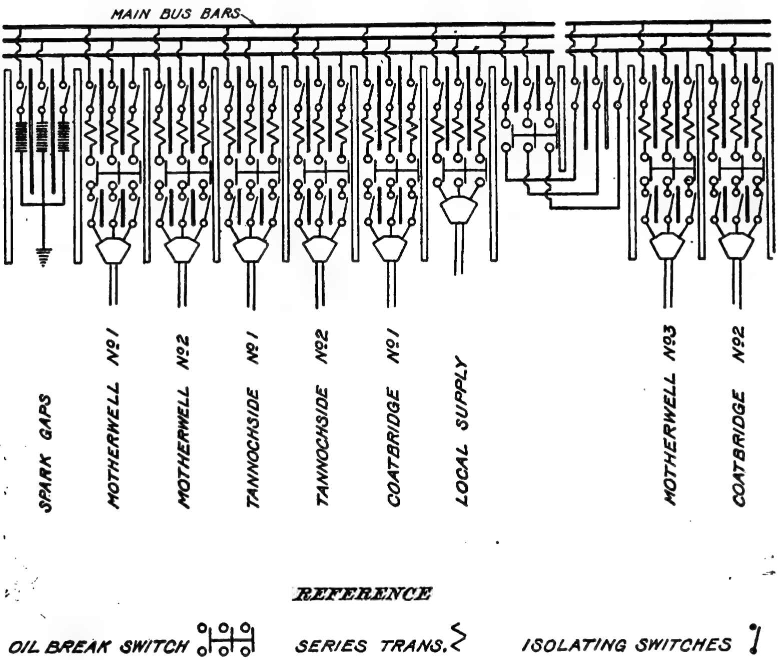


FIG. 4.

volts on the star-connected secondary side. The star-point is brought out and connected to the neutral of the 4-core low-tension distribution cables. Lighting circuits are connected between phase and neutral. As a general rule current is supplied at 25-cycles 400-volt 3-phase. In some cases, however, special conditions have had to be met and current furnished at a different voltage to meet these conditions. Bulk and large supplies at E.H.T. 10,000 to 11,000 volts are given to several of the company's consumers, notably the Coatbridge and Airdrie Electricity Supply Company, Ltd.; Messrs. John Brown, Ltd., Clydebank; Babcock and Wilcox, Ltd., Renfrew; Coltness Iron Company, Ltd.,

Newmains; Smith and McLean, Ltd., Gartcosh, and several others. In the case of the bulk supply delivered to the Burgh of Wishaw, rotary converters are installed, and the energy is metered as direct current. Similar current is also supplied to the Lanarkshire Tramways Company at Wishaw and Uddingston sub-stations. As a rule where rotary converters or motor-generators are used these are installed by the customers at their own expense and for their own convenience. The general arrangement of two typical sub-station equipments is shown in Figs. 4 and 5.

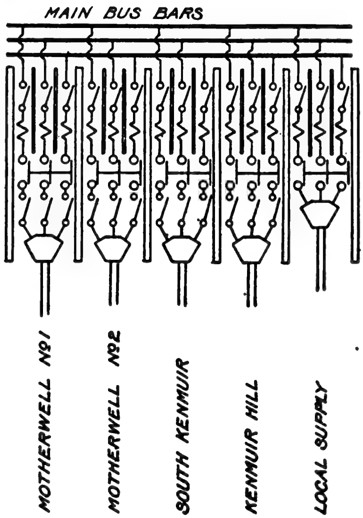


FIG. 5.

Referring to the growth of the company's output at the beginning of 1908, 12,400 H.P. was connected to their mains, and the following shows subsequent development:—

January, 1909	19,500	H.P. connected.
„ 1910	27,000	„ „
„ 1911	36,600	„ „
„ 1912	46,500	„ „

and on the 1st May, 1912, this had been increased by some 6,000 H.P. The 46,500 H.P. which was connected to the company's mains at the beginning of this year consisted of 43,500 H.P. in motors, etc., and the equivalent of 3,000 H.P. in lighting. About 2,200 H.P. of this latter represents shop and domestic lighting and heating (exclusive of lighting connected with bulk supply), and the remaining 800 H.P. represents lighting used in works where power is supplied. It will be observed

that with such a small proportion of lighting (less than 8 per cent. of the whole load) the company have no appreciable lighting peak at any time during the year. Fig. 6 illustrates the connections to mains month by month for four years from the beginning of 1908 to the end of 1911.

The diversity factor is also noteworthy. The highest peak reached by the combined stations during 1911 was 12,500 k.w., this being only 27 per cent. of the killowatts connected at that time. The sum of the highest observed loads on the stations taken separately each week is invariably much higher than the actual demand of the two stations when running in parallel. This difference has at times exceeded 1,000 k.w. One

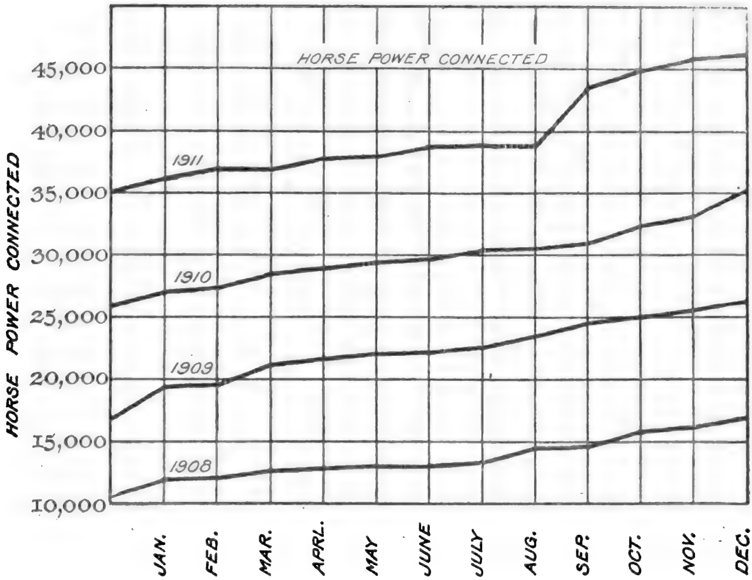


FIG. 6.

reason for this is the different class of works being supplied from each power house, and the different hours of working, stoppages for meals, etc., between the districts. At Yoker the supply is largely to shipyards and engineering works, whereas at Motherwell iron and steel works and collieries are the largest consumers. The night load at Motherwell is, as a rule, not less than 20 per cent. below the day load, and the week-end load is never below $\frac{1}{3}$ of the ordinary day load. The load factor on units generated at Motherwell is frequently 65 per cent. and over during a complete week of 168 hours, whilst at Yoker the load factor on similar conditions is frequently 40 per cent. The combined load factor of the two stations sometimes reaches 58 per cent. over a week. It is remarkable to observe the similarity in rise and fall of the

combined outputs over the past four years, and Fig. 7 illustrates the monthly output of the power houses from the beginning of 1908 to the end of 1911. The particular feature is the similarity in contour of these lines. Some notes contrasting the operating conditions in the early stages of the company's career and those existing to-day may be of interest. By referring to some of the old records it was found that at the beginning of 1906 the coal consumption at Yoker was 35 lbs. per unit generated, and at Motherwell 49 lbs. per unit generated. In the beginning of the year 1907 there was a maximum demand on Yoker of 480 k.w. and at Motherwell of 570, and even with a 40 per cent. load

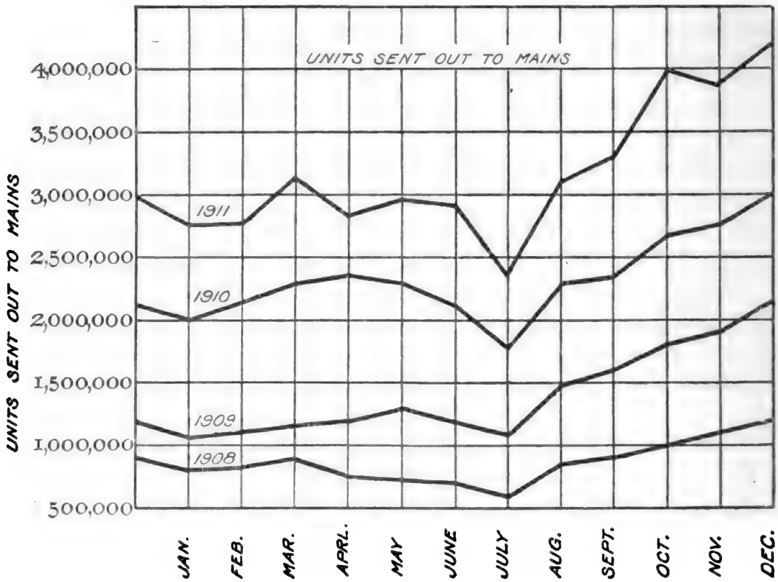


FIG. 7.

factor over the week the coal consumption was between 10 and 11 lbs. per unit. At the beginning of this year the coal consumption per unit generated was under 3 lbs. per kilowatt-hour for both power houses, and it is confidently expected that a further reduction will take place when the new Yoker plant is in regular commission, and the full benefit is being derived from the installation of the storage batteries and the closing down of the reciprocating engines already referred to.

The company appears to have good prospects for the future. There is no reason to doubt that the same steady rate of progress will be continued for some time. The area served is a good field for the investment of capital, and new works are continually being started, besides which many steam and other plants which have been installed in

collieries, iron and steel works, shipyards, etc., many years, are gradually becoming obsolete, and there is a growing tendency in the district, as in fact all over Great Britain, for power users to take their supply (with its many advantages) from a power supply authority.

One of the company's largest bulk consumers is the Coatbridge and Airdrie Electric Supply Company, Ltd. Previous to 1908 they generated their own current by steam, and during the past six years their output has increased by 700 per cent., their revenue shows an increase of nearly 300 per cent., whilst gross profits have increased 100 per cent.

During the recent strike amongst the coal-miners the company were enabled to maintain their supply to all their consumers until the strike was settled without having to purchase any additional fuel, the company having carried a large reserve of coal for some years in case of such a contingency. In many cases considerable additional load was connected to the company's mains, and many works were enabled to keep in full operation that otherwise would have been completely shut down. The good effects of this have already been shown by the increased demands on the company for connection.

Discussion.

Mr. W. McWhirter: The author's paper does not give room for criticism, but there is much additional information which the author could give perhaps in his reply. The condensing arrangements as now in use at Motherwell show clearly the economical progress of the works, and the saving in power due to the combinations of water turbine and pumps must amply repay the expenditure incurred. The load factor of 60 per cent. is one which any engineer might be pleased with, and there is no doubt the coupling up of Yoker and Motherwell stations and the diverse power-users alone made this possible. The Clyde Valley Company deserve credit for the admirable supply they were able to maintain during the coal strike, and it is pleasing to notice that not only were they able to keep up the supply to all consumers, but they had ample reserves which would have allowed them to increase their load had occasion required. I might also add that the supply maintained not only by the Clyde Valley Company, but also by the Glasgow Corporation Electricity Department, enabled manufacturers in Glasgow and district to carry on at full power during the whole period of the strike. Power users must have realised that many thousands were saved from being forced to join the ranks of the unemployed, and great loss and much suffering avoided owing to the splendid service given by the power companies. Mr. McWhirter.

Mr. W. W. Lackie: The author's paper does not lend itself to discussion or criticism, as it is mainly descriptive. It lets us see what some of us have known for a considerable time, namely, that the Clyde Valley Company is to play an important part in the industrial life of the Clyde estuary and district. The company have undoubtedly performed a signal service to the whole electrical industry, by showing that electrical energy taken from a large central power-house is a thoroughly economical Mr. Lackie.

Mr. Lackie. and efficient prime mover. As Mr. McWhirter has pointed out, I think we must all congratulate the company on the splendid position they maintained during the coal strike. Their uninterrupted supply during that time not only kept many mines in a state which enabled a direct return to work to be made whenever the strike was over, but it showed to many large manufacturers for the first time the possibilities of the electric drive. There are two points in the paper of particular interest to me. The first is in connection with coal consumption. We had in Glasgow in the early days an experience very similar to what is described in the paper, but I must say we have never managed to burn 35 to 49 lbs. of coal per kilowatt-hour. Our working figure was 28¾ lbs. in 1892, and this was reduced to 15 lbs. in 1893. Since then we have come steadily down until to-day we regularly run at a figure of 3 lbs. The other point I am interested in is the item of underground mains. I have never been able to understand why stamped steel bridge-pieces should continue to be used, as they seem to be simply inviting trouble by giving contact between the lead of the armouring of the cable and the surrounding soil. I believe the author is correct in saying that for outlying districts where the cartage and transport charges on the various materials amount to quite a large sum, a specially prepared armoured cable laid direct in the ground will be found cheapest. But where cartage and transport do not run to a big sum, it will be found that the cost of wooden troughing and pitch does not exceed the cost of armouring. We had trouble with burning accidents when we used bitumen for running up our cables, but I cannot remember ever hearing of a single burning accident with pitch. The fact is that pitch has such a low specific heat that a workman can put his hand into a bucket of hot pitch and the pitch will harden on his hand and do no harm. I would just like to add that the author's paper would have been even more interesting if he had given us some details of the capital cost for different items, such as land, buildings, machinery, mains, etc.

Mr. J. A. Robertson. Mr. J. A. ROBERTSON: I had the opportunity of visiting the Clyde Valley Power Company's stations recently and was very much impressed with the alterations which have been carried out, and especially with the new cooling-water arrangement. When the new plant is compared with the original lay-out, the improved economy in the author's results will be easily understood. He has been very frank in telling us how his company have scrapped plant from time to time and replaced it with something more economical. Municipal engineers who have to keep in mind the requirements of a sinking fund will appreciate the advantage in having a private company to deal with. There are many points in the original design of the station which might be criticised, but most of these have been removed by recent alterations. At the Motherwell station, however, it seems strange that only one chimney has been built and that it was necessary to shut the station down in order to clean the flues. I would like to ask the author if he has found any trouble with the low periodicity

of 25 cycles. It has always appeared to me that a higher periodicity ought to have been selected by the power companies. I would also like to know what the efficiency of his system is, viz., the ratio of units sold to units generated. I must congratulate the author on the large reduction in his fuel costs and on the rapid increase in output. The paper is one which contains a good deal of inside information, which should be very useful to all central station engineers. **Mr. J. A. Robertson**

Mr. J. M. M. MUNRO: The author's advance from 49 lbs. to 3 lbs. of fuel per unit generated may suggest bad design to begin with; but the very high initial figure was doubtless due to the small load on the big plant, and it would rapidly fall as the load improved. The more recent gain is due, partly to the continued increase of plant and demand, but also to the accumulating suggestions of experience and ingenuity. I particularly admired the application of the water turbine to the pump shaft at Motherwell, leaving the electric motor to meet only the friction losses. The improved load factors got by interconnecting the two power stations is noteworthy as an argument for large districts of supply. The only criticism I wish to make is to say that I should have been glad of more figures as to capital, working, and distributing costs. **Mr. Munro**

Mr. A. P. ROBERTSON: There is one point I notice in connection with the Clydebank supply and Mr. J. A. Robertson has mentioned it. The periodicity there was 50 cycles; in other places it was 25. I would like to ask the author if there is any difficulty with consumers owing to the low periodicity. I have noticed it myself in one or two places where arc lamps seemed to flicker very badly. These have since been replaced by metallic filament lamps, but they also have a decided flicker. **Mr. A. P. Robertson.**

Mr. F. J. LAUNCHBURY: I should like to ask the author if the overhead E.H.T. and telephone lines are transposed at regular intervals. If not, is any difficulty experienced due to induction in the telephone lines? It would appear to me from the photographs showing the relative arrangements of E.H.T. and telephone lines, that trouble due to induction is certain to occur on the telephone system, particularly under "fault" conditions. Mr. Robertson has raised a point regarding the efficiency of 25-period lighting, stating that it is not at all satisfactory —more especially for arc lighting. It would be futile for me to say that 25 periods is a good frequency for lighting purposes, but at the same time my experience has been that arc lighting and incandescent lighting at 25 periods is quite satisfactory for all practical purposes. We have quite a number of 25-period arc-lighting installations in our area giving perfect satisfaction to all concerned. It is almost impossible to detect the frequency flicker by looking directly at the arc lamp, and it is certainly quite impossible to detect it when looking at the work or machines upon which the light from the lamp is shining. Care should, however, be exercised in choosing arc lamps for this frequency if the best results are to be obtained. With an ordinary incandescent lamp hung vertically it is possible to see a slight flicker due to the frequency **Mr. Launchbury.**

Mr. Launchbury. in the lamp itself, but when reading or working directly beneath such a lamp, the flicker is almost imperceptible.

Mr. MacKenzie. Mr. J. D. MacKenzie: I would like to suggest that the author might have dealt at some length with the financial aspects, such as the average price per unit and the average cost per unit. That I think would have completed our information with regard to the matter. There is also one other point. I presume the Clyde Valley Company's system is having power consumers connected so rapidly that they have little time or desire to canvass for lighting except in bulk. Has no attempt been made to increase the demand for lighting among the smaller individual consumers? It would be interesting to learn what has been done or suggested to bring small shops and houses as consumers on to the system.

Mr. Stevenson. Mr. George Stevenson: A previous speaker has referred to the fact that the generating plant of most power supply companies was designed for 25 cycles, but I think this is not the case; at any rate the Newcastle Electric Supply and Allied Companies generate at 40 cycles. Coming to the paper itself, I am more particularly interested in the Clyde Valley systems, so far as it affects the consumers' plant. The similarity of the curves referred to by the author on page 798 can, I think, be easily explained when it is remembered that a large number of new motors are installed during the Glasgow Fair holidays, this being the most convenient time to make a change-over from steam to electric driving. Thus the sudden rise in the load from July on to the end of the year is readily accounted for. Some electric supply concerns—notably corporations—restrict their consumers to certain sizes of squirrel-cage motors, and they also insist on low-voltage release devices being fitted to the starting gear. I should be glad to hear whether the author imposes any similar conditions, and also what is the largest size of squirrel-cage motor installed on the Clyde Valley mains. Then with regard to the "earthing" of the neutral point, I understand that this is done at the consumers' terminals, on the low-tension side, through a 25- or 30-ampere fuse, and also direct at the power station, on the generators. In view of the fact that the Home Office is now recommending leakage protective apparatus for colliery installations, and as these involve earthing the neutral through a resistance, it would be interesting to know whether the author would consent to this being done. With regard to the method of earthing at the power station, may I ask what precautions are taken to avoid the heavy circulating currents between the generators which take place under certain circumstances, when earthing in this manner is resorted to? One other point: Is any cable-charging device used when switching in long feeders?

Mr. Starr. Mr. D. A. Starr (*in reply*): I may say we do not push for lighting very vigorously, but we take on all the customers that come our way, and have given current for lighting to people in many parts of the country where even gas was not available.

Mr. Lackie referred to coal consumption. Well, in speaking of

efficiency I think he was referring to a reasonable size of generating unit proportionate to its load. In Motherwell we not only had to run a 2,000-k.w. unit on a load averaging from 100 to 150 k.w., but we had to run about 150 H.P. of auxiliary plant to keep that going. Mr. Starr.

With regard to the financial part which was omitted from the paper, I am afraid when it comes to dealing with financial matters, such as costs, etc., we would require to make a rule debarring consumers, either present or prospective, from being present, for such figures are almost invariably misunderstood.

Mr. J. A. Robertson would like to have some information about distribution. Speaking without having the actual figures before me, we send out about 95 per cent. of the current generated. From 4½ per cent. to 6 per cent. is used in the works, and we sell about 85 per cent. of what is sent out, the rest of course being units lost in distribution. It depends very largely on the number of transformers connected to the mains, and the number of these being continuously energised on the system.

With regard to the periodicity at Clydebank, I am afraid the blame will have to be thrown on our friends, the consulting engineers.

On the other points I may say we chose the smaller evil at the outset. Since then a great many people there who had started on 50-period supply have been changed over to 25-period, and they do not know the difference.

HOMOPOLAR GENERATORS.

By Ernest W. Moss and J. Mould, Students.

(Abstract of paper read before the Students' Section *on 24th April,* 1912.)

Introduction.—Homopolar generators have in the past only had a very restricted field of use, it having been found until quite recently to be both commercially and practically impossible to use this type of machine for any but low-voltage electrolytic work. There were three main reasons for such limited use, viz.:—

1. Uncertainty as to the magnetic and electrical conditions existing in the machines.
2. The fact that the homopolar machine is essentially a high-speed machine.
3. The difficulty of collecting large currents at high peripheral speeds.

In these days of large turbine-driven units, assuming that difficulty No. 3 can be overcome, the most efficient turbine speed becomes more nearly that of the most efficient generator speed, with certain limitations discussed later in the paper, which is not the case with commutator machines, and hence the homopolar appears to have some prospect of future success in this sphere of work.

The history of homopolar generators commences with the first dynamo electric machine, namely Faraday's famous disc machine. Faraday also proposed various modifications of his first machine. From that time many men invented types of homopolar generators, amongst whom were Tucker, Weber, Varley, Silvanus P. Thompson, Forbes, Munro, Brown, and others.

Types.—There are two main classes of homopolar machines, namely:—

1. *The disc type*, in which the arrangement is such that the currents are generated in the armature in a direction at right angles to the axis of rotation, the armature consequently being in the form of a disc, and
2. *The cylinder type*, in which the arrangement is such that the currents are generated in the armature in a direction parallel to the axis of rotation, the armature consequently being in the form of a cylinder.

The disc type of machine has never been successful, there being many difficulties in the construction of such machines, and it is to the cylinder type to which attention must be paid for the construction of machines of large output.

Homopolar dynamos met with no real success until Dr. J. E. Noeggerath built his now famous machine of the cylinder type, and the development of this type is entirely due to him. This he described in a paper * read before the American Institute of Electrical Engineers in 1905. The machine discussed in the paper was a 300-k.w. 500-volt turbine-driven machine of the cylinder type.

A homopolar generator designed by Mr. R. H. Barbour † was exhibited, and caused an amount of interest at the recent electrical exhibition. The machine gave 50 k.w. at 100 volts and 3,500 revs. per minute.

Barbour's machine is very similar to that of Noeggerath. The conductors are placed in the slots running through the armature and are connected at each end to slip-rings. The slip-rings and armature are bolted together by insulated bolts running therethrough. The bolts are alternate with the armature conductors.

The brush-gear designed by Mr. Barbour appears to be very successful. Each slip-ring is formed with a hollow surface and in the said hollow surface bears the brush, which consists of a flexible copper core wound or armoured with German silver wire. The armouring makes good contact and protects the core from wear. The brushes are held in place, and pressure between them and the rings is obtained by the aid of springs and adjusting nuts.

A small amount of lubricant is allowed to feed on to the brushes.

This form of brush-gear from Mr. Barbour's published results of tests appears to be very successful, and he claims that it "has only half the losses per ampere collected of any other." One important advantage is that a much larger portion of the surface of the ring is utilised from which to collect current.

The frame conductors for connecting the armature conductors in series or as required are carried outside the machine in contradistinction to the Noeggerath machine.

It is proposed now to deal as far as possible with the difficulties occurring in the design of homopolar machines for modern turbine speeds and to show that the homopolar does not compare unfavourably with the commutator machine for moderate voltage work.

Design.—Proceeding first with the design of homopolars, it is desirable, owing to the lack of previous experience, to work the design by the use of output coefficients. For this reason it is advisable to use the expression first given by Esson for continuous-current machines.

$$d^2 l = \frac{\text{K.W.}}{\text{R.P.M.}} \times \xi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

* *Transactions of the American Institute of Electrical Engineers*, vol. 24, p. 1, 1905.
† *Engineering*, vol. 92, p. 318, 1911.

This expression states that the product of diameter squared and length is equal to the output in kilowatts per revolution multiplied by a certain constant ξ known as the Esson coefficient.

ξ has of course a fixed value for machines of a fixed type having given definite values for B, q, and ψ, and for ordinary commutator machines is obtained from the following expression :—

$$\xi = \frac{60 \cdot 8 \times 10^{10}}{B \times q \times \psi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where—

B = flux density in the gap.

q = specific loading of armature core in ampere conductors per inch of periphery.

ψ = ratio of pole arc to pole-pitch.

It will be obvious at once that this coefficient ξ is applicable to homopolar machines, and indeed due to the fact that in homopolars ψ always has a value of unity the formula becomes—

$$\xi = \frac{60 \cdot 8 \times 10^{10}}{B \times q} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

This simplifies the first steps of the electrical design of the machine, as when one has determined what are suitable values for B and q for any type or size of machine the overall dimensions of the core are fixed.

The most practical form of homopolar is that shown in Fig. 3. This machine, besides many other mechanical advantages, has the advantage of being free from end thrust, and has been the type chiefly adopted in practice.

Speed.—Machines of the Noeggerath type have certain limitations as to speed which we propose to investigate here.

For machines of small output and therefore of small core dimensions a particularly high speed is most favourable, because assuming the material of the core to be worked at its maximum surface speed the core assumes a better proportion than it would if worked at a lower speed—that is, the diameter is reduced to a better value. But while the speed greatly influences the design of the machine in small units it is not nearly so important a factor as it is in the case of large units.

In the case of large units, assuming that the values of B, q, and v are fixed, there exists a critical speed above which it is impossible to design a machine of a particular output.

It will be obvious that such a speed does exist when it is remembered that if the length of the core is increased above a certain fixed value it becomes impossible to pass the flux through the rings.

The speed at which it is most economical to work a homopolar, and above which it cannot be designed for any particular output is obtained as follows :—

As the flux in the armature after cutting the conductors divides, half

going in one direction down the core and half in the other direction assuming equal saturation in all parts of the core, the following equation will hold good for a machine in which the magnetic properties are the same in all directions :—

$$\frac{\pi d l}{2} = \frac{\pi d^2}{4}$$

$$\therefore \quad 2l = d \quad \ldots \ldots \ldots \ldots \quad (4)$$

where l is the length and d the diameter of the armature core. But assuming the machine to be worked at a surface speed $= v$—

$$d = \frac{v \times 12}{\text{R.P.M.} \times \pi} \quad \ldots \ldots \ldots \ldots \quad (5)$$

and from equation (1) it will be seen that—

$$l = \frac{\text{K.W.}}{\text{R.P.M.}} \times \xi \times \frac{l}{d^2} \quad \ldots \ldots \ldots \quad (6)$$

Now in (6) substitute the value obtained for d in (5), and we get—

$$l = \frac{\text{K.W.}}{\text{R.P.M.}} \times \xi \times \frac{(\text{R.P.M.} \times \pi)^2}{(v \times 12)^2} \quad \ldots \ldots \quad (7)$$

$$\therefore \quad l = \frac{\text{K.W.}}{v^2 \times 12^2} \times \xi \times \frac{\text{R.P.M.} \times \pi^2}{l} \quad \ldots \ldots \quad (8)$$

Substituting in (4) the value obtained for d in (5) we get—

$$2 \times l = \frac{v \times 12}{\text{R.P.M.} \times \pi} \quad \ldots \ldots \ldots \quad (9)$$

$$\therefore \quad l = \frac{v \times 6}{\text{R.P.M.} \times \pi} \quad \ldots \ldots \ldots \quad (10)$$

Equating (10) to (8) we get—

$$\frac{v \times 6}{\text{R.P.M.} \times \pi} = \frac{\text{K.W.}}{v^2 \times 12^2} \times \frac{\xi}{l} \times \frac{\text{R.P.M.} \times \pi^2}{l} \quad \ldots \ldots \quad (11)$$

$$\therefore \quad \text{R.P.M.}^2 = \frac{v \times 6 \times v^2 \times 12}{\text{K.W.} \times \xi \times \pi^2 \times \pi}$$

$$\therefore \quad \text{R.P.M.} = \sqrt{\frac{v^3 \times 864}{\text{K.W.} \times \xi \times \pi^3}} \quad \ldots \ldots \ldots \ldots \quad (12)$$

$$\text{R.P.M.} = \sqrt{\frac{v^3 \times 27{\cdot}9}{\text{K.W.} \times \xi}} \quad \ldots \ldots \ldots \ldots \ldots \quad (13)$$

It would be found in practice more convenient to write the expression obtained in (13) in the following form :—

$$\text{R.P.M.} = \frac{1}{\text{K.W.}^{\frac{1}{2}}} \times \mu \quad \ldots \ldots \ldots \quad (14)$$

μ being the sign chosen by the authors to denote the coefficient—

$$\left(\frac{v^3 \times 27{\cdot}9}{\xi}\right)^{\frac{1}{2}}.$$

The value given in (13) is therefore the maximum speed at which a homopolar machine of the Noegerrath type having a given surface speed can be most economically designed to run and with a view to simplifying the design of machines curves connecting R.P.M. and K.W. for various values of μ, and for a peripheral speed of 20,000 ft./minute have been plotted in Fig. 1 from the figures in Table III. The values of μ chosen have been worked and tabulated in Table II., from values of ξ chosen from Table I. calculated for various values of B and q. It will be seen that the value of v chosen in the case of large units is governed not only by mechanical considerations

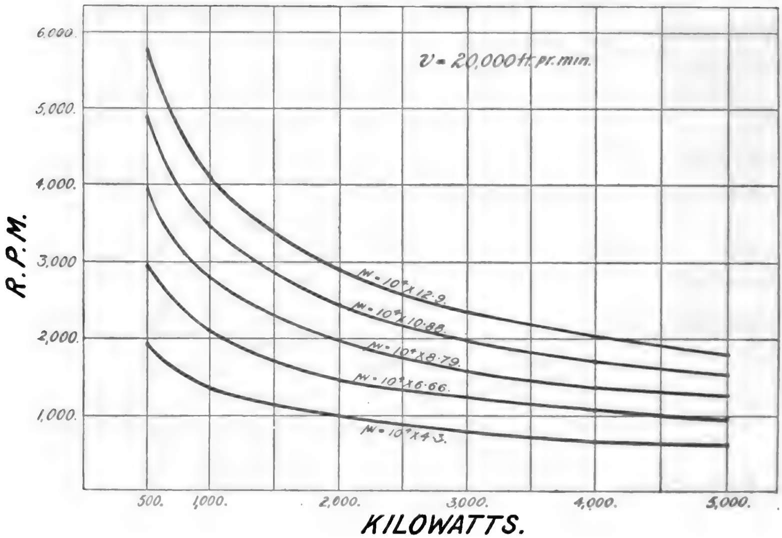


FIG. 1.

as is generally the case, but also by the electrical and magnetic conditions already existing.

Specific Loading.—There appears to be no reason why the specific loading in fairly large units should not be pushed as far as 300- to 400-ampere conductors per inch of periphery, though in machines yet built it is mostly below this value.

Flux Density in the Gap.—Owing to the practical absence of iron losses it is quite admissible to make the gap density much higher than that usually obtaining in electrical machinery, and if the core be of good cast-steel densities of from 70,000 to 90,000 lines per square inch may be used provided this does not necessitate an excessive amount of field copper.

Current Collection and Slip-ring Losses.—The difficulty of collecting currents from surfaces moving with a high peripheral velocity has in

the past been a great bar to the progress of the homopolar machine. In modern machines of this type practically 60 per cent. of the total loss in the machine occurs at the points of collection, and it is safe to say that were it not for this loss the homopolar would be one of the most efficient of electrical machines.

It is impossible to calculate the losses at a sliding contact moving at a high velocity due to the fact that the power wasted does not follow a simple I^2R law, or any other simple law.

The matter, however, has been tackled experimentally by several investigators, including Cottle and Rutherford,* Barbour,† and Dr. J. R. Noeggerath.‡

In Dr. Noeggerath's classical memoir the subject of ring losses is fully gone into, and a large amount of very valuable information

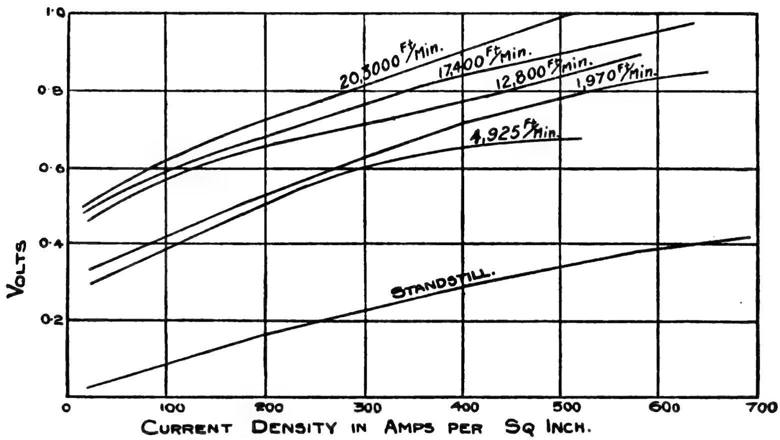


FIG. 2.

obtained on large homopolar machines is given. He carried out his experiments on steel rings and copper rings, the current being collected by brushes consisting of strips of steel and bronze laminations.

Considering the question of slip-ring losses from the designer's point of view it is interesting to examine first the variation of the pressure drop at the contact with different current densities and different peripheral speeds. Fig. 2 shows this clearly, and it is interesting to note that the curves do not vary much from a pure C R law, a constant being added to compensate for each different surface speed.

* *Journal of the Institution of Electrical Engineers*, vol. 45, p. 679.

† *Engineering*, vol. 92, p. 318, 1911.

‡ "Ueber die Stromabnahme mit besonderer Berücksichtigung hohar Gaschwindigkeiten" (R. Oldenbourg, Munich).

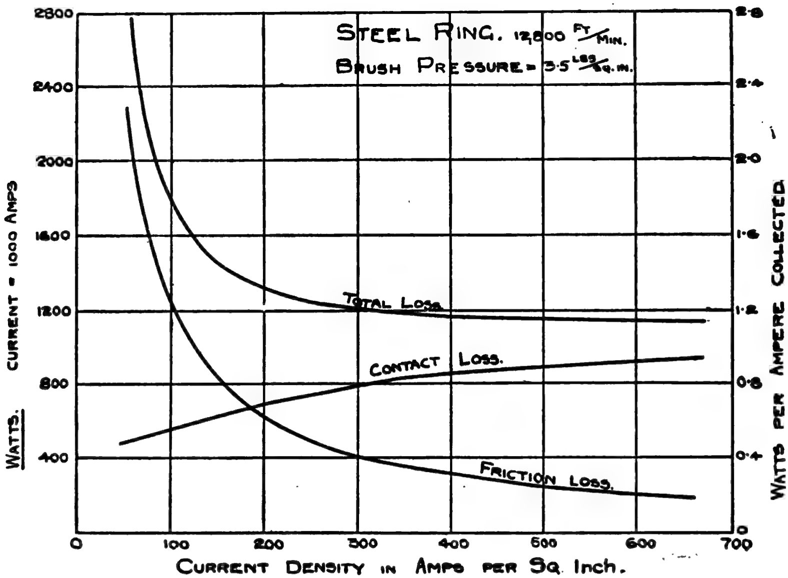

STEEL RING. 12,800 FT/MIN.
BRUSH PRESSURE = 3·5 LBS/SQ. IN.
WATTS. CURRENT = 1000 AMPS
WATTS PER AMPERE COLLECTED
TOTAL LOSS.
CONTACT LOSS.
FRICTION LOSS.
2800
2400
2000
1600
1200
800
400
2·8
2·4
2·0
1·6
1·2
0·8
0·4
0
0
100
200
300
400
500
600
700
CURRENT DENSITY IN AMPS PER SQ. Inch.

FIG. 3.

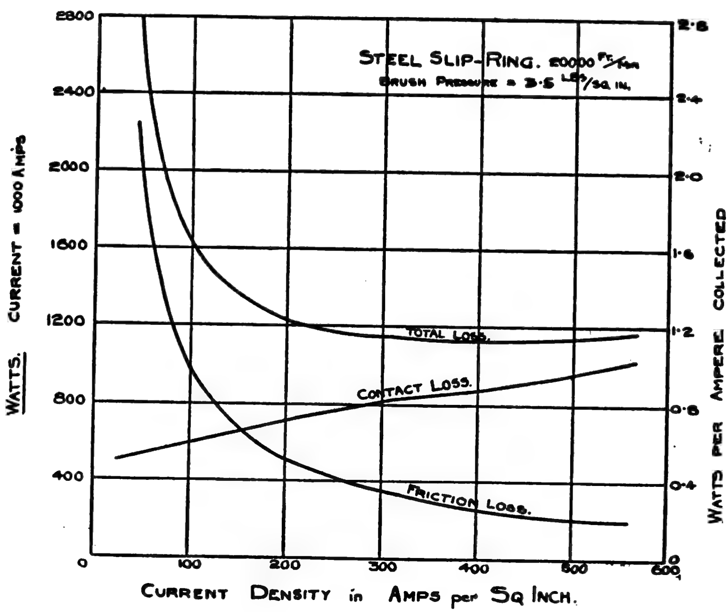

STEEL SLIP-RING. 20000 FT/MIN
BRUSH PRESSURE = 3·5 LBS/SQ. IN.
WATTS. CURRENT = 1000 AMPS
WATTS PER AMPERE COLLECTED
TOTAL LOSS.
CONTACT LOSS.
FRICTION LOSS.
2800
2400
2000
1600
1200
800
400
2·8
2·4
2·0
1·6
1·2
0·8
0·4
0
0
100
200
300
400
500
600
CURRENT DENSITY in AMPS per SQ INCH.

FIG. 4.

Considering now the total loss, Figs. 3 and 4, it is found that while the contact loss rises with the current density yet the friction loss is reduced at a very rapid rate as the current density increases. It is found advisable to collect current from the rings at a density of from 100 amperes per square inch to 260 amperes per square inch. The lower limit is fixed by considerations of the total losses per ampere collected, and the upper limit, while giving a less total loss per ampere collected, is fixed by practical considerations as to sparking, heating of rings, and the life of the ring and brushes.

Next examining the variation of the total loss with the peripheral speed, Fig. 5 shows the variation of the total loss with the surface speed, and from this curve it would appear to be more favourable to work at a peripheral speed somewhere in the region of 20,000 ft.

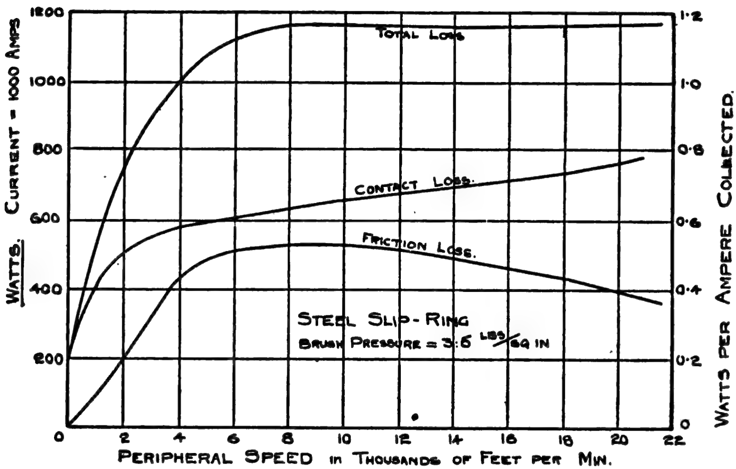


Fig. 5.

per minute. This peripheral speed also appears to be the most favourable when considering the design from the point of view of total loss.

The total loss will be found plotted against surface speed in Figs. 5 and 6, and it should be noted that after a speed of 8,000 ft. per minute is reached the total loss does not appreciably increase.

From an examination of these curves, therefore, one takes it that a current density of about 200 amperes per square inch at the contact, and a peripheral speed of about 20,000 ft. per minute, are desirable in a well-ventilated machine.

The question of the most suitable pressure at which to use the brushes has been worked at experimentally by several investigators, and as a result of their work it would appear that the brush pressure ought to be somewhere in the region of 3·5 lbs. per square inch. It will be

noticed that this pressure was used in the investigations, the results of which are given in the curves given in this paper.

With regard to the temperature rise of the rings, it will be again noted that a high peripheral speed is desirable in order to obtain good ventilation.

There is in the homopolar machine an entirely different distribution of losses to that usually obtained in electrical machines.

Owing to the absence of core loss there is less ventilation needed in the rotor of the machine, but the fact that the ring losses form such a large percentage of the total loss, renders it necessary that a very efficient system of ring ventilation be provided.

The ventilation of the rings is therefore made easier if the peripheral speed be high.

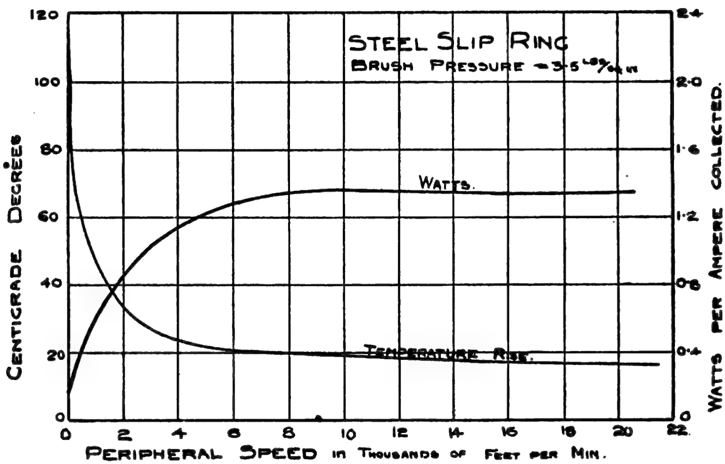


FIG. 6.

Fig. 6, which shows curves connecting temperature and peripheral speed of slip-rings, emphasises this fact, and it should be noted that while the total loss is here increased to seven times its minimum value, yet the temperature rise is reduced from 100° C. when running slowly to 16° C. when running at 20,000 ft. per minute.

The curves of the brush losses given by the authors are plotted from the values obtained by Dr. J. E. Noeggerath, from tests on a 2,000-k.w. machine, and published in his dissertation "Ueber die Stromabnahme." *

Reactions.—The homopolar generator is found in practice to regulate much better than the average modern continuous-current machine designed with economical constants.

* "Ueber die Stromabnahme mit besonderer Berücksichtigung hoher Geschwindigkeiten" (R. Oldenbourg, Munich).

Two 500-k.w. homopolar machines built by the G.E.C. of America are working in parallel on a 3-wire system, the third wire being connected to the centre slip-ring of each machine. These machines are said to regulate excellently without other auxiliary machinery such as balancers, etc.

The two principal reactions in homopolars are: (1) ring reactions, and (2) distortion of the main flux due to the current carried by the armature conductors.

Considering first the ring reactions, in Fig. 7, which shows diagrammatically a cylinder-type machine, it will be seen that the total current carried by the conductor splits up when it enters the ring part flowing to the brush along the path marked B, and part along the path marked B'.

One side of the ring will therefore tend to strengthen the main flux, while the other side will tend to reduce it. It is, however, impossible

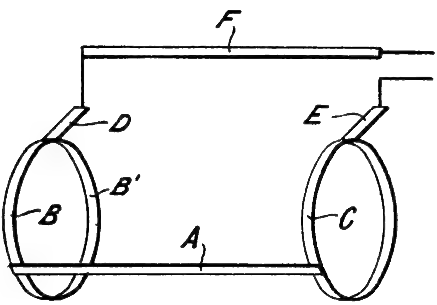


FIG. 7.

for this ring reaction to strengthen the main flux due to the fact that it is generally found necessary to work the core up to very nearly its maximum flux density. The other side is, however, found to produce some small decrease of the total flux, but the decrease is not sufficient to prove troublesome.

Ring reactions can, however, be totally eliminated if a particular arrangement of the brushes be adopted, and it should be here pointed out that the reaction is also considerably reduced if the machine be built with several conductors in parallel and their points of connection to the ring be made at places equidistant round the ring circumference.

The second and more serious armature reaction is that caused by the current in the conductors themselves.

In the ideal armature the conductors would be so arranged that there would be a uniform flow of current all round the circumference of the armature, that is to say, $\frac{di}{dl}$ would be equal to a constant, where di represents an element of current and dl an element of the circumference.

The armature will therefore in the ideal case take the form of a cylindrical shell of current, and the effect of this will be to produce a circular flux round the armature itself and concentric with it. Referring to Fig. 8, it will be seen that in the practical form where the current is concentrated at certain points round the periphery any particular conductor C will tend to produce its own circular flux round itself marked F in the diagram, and due to the moderately close proximity of the conductors to one another the result will be a reaction very similar to that obtained in the ideal case, *i.e.*, conditions will tend to produce a circular flux E concentric with the armature itself.

If precautions are not taken this reaction may seriously affect the performance of the machine.

The first effect, and perhaps the most serious, of this reaction will be to cause severe distortion of the main flux, the distortion being, of

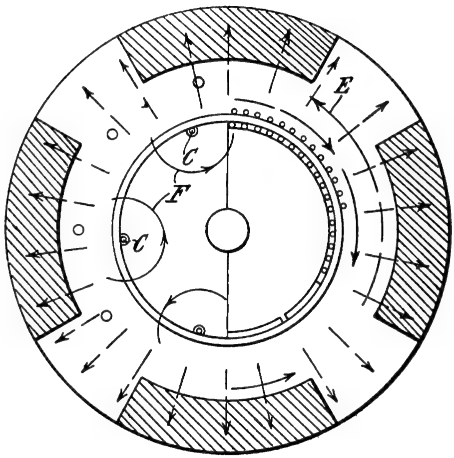


FIG. 8.

course, proportional to the specific electric loading of the armature, and as this would cause the flux density at any particular point of the armature circumference to vary several times during each revolution, and hence many times per second, a very considerable iron loss would be introduced which would affect the efficiency to a serious extent.

This distortion will, of course, be much reduced if the iron just at the surface of the armature be pushed to a high degree of saturation, and as there is no reason why this should not be done, it is in the case of small machines not necessary to take any further precautions.

Barbour has, however, in his machines constricted the carcass at points Y^1, Y^2, Y^3, and Y^4 shown in Fig. 9, and it should be noted that this will rather aggravate matters, as it will cause severe bunching of the flux at the points of stricture, and a higher maximum density will

be obtained at certain points round the periphery, the effect of which will be therefore to give a considerable iron loss.

In large machines the only way to overcome this reaction is to compensate the machine in a similar manner to that in which high-speed continuous-current machines are compensated at the present time. The compensating winding consists of a number of conductors let into slots in the pole-face and connected in series with the armature.

These conductors will carry current in the same direction, and may serve to connect the slip-rings in series.

In most cases it will be found necessary to provide a one-to-one compensation.

Another effect of this armature reaction, if it be not compensated, will be to cause bad regulation as due to the increase in the length of the path of the main flux due to the distortion the total flux may become somewhat reduced.

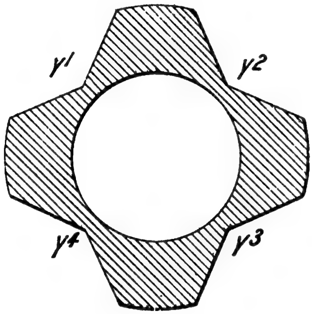


Fig. 9.

Conclusion.—Owing to the fact that very few large homopolar machines have been built it is very difficult to obtain accurate information as to their performance.

The authors would, however, point out that the results obtained with the 300-k.w. machine which are given in this paper do not compare at all unfavourably with modern continuous-current commutator machine practice, and as in large machines one may look for a considerable reduction to the number of rings the efficiency ought to be increased to a considerable extent, and it is safe to say that one may look for a reduction in the losses of from 15 to 20 per cent.

As will be seen from the brush-loss curves, the difficulty of brush losses is being gradually overcome, and while it would appear unlikely that the current can ever be collected as efficiently in these machines as in commutator machines yet it is quite possible that the net efficiency will in the case of large machines be much greater.

With regard to the question of cost it is stated by Noeggerath* that the homopolar is about on the same level as the commutator machine, and at the same time it can be constructed with approximately the same weight.

The obvious simplicity of the homopolar goes a long way towards considerable reduction of upkeep charges, and when carefully designed the absence of current-collecting troubles tend to place it in a much better position than the commutator machine.

* *Transactions of the American Institute of Electrical Engineers*, vol. 24, p. 1, 1905.

APPENDIX.

In order to show the feasibility of designing a large homopolar with the densities and constants advocated in this paper, the authors wish to give a rough idea of the dimensions and general design of such a machine.

It must, of course, be understood that the design is only a rough provisional step to the design which would be obtained were one about to build the machine, but it is at the same time hoped that this rough outline of the design will show clearly the general lines upon which such a machine would be constructed.

The authors propose to give the main dimensions of a machine designed to have an output of 5,000 k.w. at a pressure of 500 volts and and a speed of 1,530 revs. per minute.

The principal dimensions and densities are :—

B_g = 81,500 lines/square inch.
q = 400 amp. cond./per inch.
v = 20,400 ft. per minute.
d = 51 in.
l = 25·5 = net iron length.
l_{total} = 29·5.
Z_s = 6 = number of sets on conductors in series.
Z_{total} = 48.
Conductors of round copper 1 in. diameter placed in closed circular holes.
Maximum tooth density = 130,000.

Slip-rings—

Number of rings	12.
Brushes per ring	8.
Current per brush	1,250 amps.
Current density in brush	250 amps./square inch.
Brush contact area...	5 sq. in.
Brush made of bronze and steel laminations :—	
Width of slip-ring	2·25 in.
Diameter of slip-ring	51 in.

Losses at Full-Load—

Ring losses	144 k.w.
Copper losses	9 „
Stray loss, windage, etc.	47 „
Total	200 k.w.

Total loss	4 per cent.
Efficiency	96 „

THE CHOICE OF MATERIAL FOR OVERHEAD LINE CONDUCTORS.

By E. V. PANNELL, Student.

(*Abstract of a paper read before the* STUDENTS' SECTION *on* 31*st January*, 1912.)

In the field of overhead power transmission at the present day, there may be said to be two active competitors as conducting materials, viz., copper and aluminium. In preference to the latter metal in its pure state, alloys have often been experimented with, and bearing in mind that the tensile strength of aluminium may be increased upwards of 60 per cent. by judicious alloying without a very great decrease in conductivity, this would seem to be justified. It is, however, found in practice that no such alloy is as resistant to corrosive effects as pure aluminium, and this advantage is sufficient to discount the use of alloys for bare overhead conductors.

The comparative physical properties of copper and aluminium have been detailed elsewhere, and need not be dwelt on at length. Such properties as are relevant to this investigation are set out in the following table :—

Properties of Copper and Aluminium Stranded Overhead Conductors.

	Copper.	Aluminium.
Relative conductivity, per cent.	100	60
Specific gravity	8·95	2·71
Relative weights for equal conductivity	100	50
Relative cross-section	100	166
Tensile strength lbs./square inch	60,000	30,000
Factor of safety	5	5
Maximum working stress ...	12,000	6,000
Modulus of elasticity	12,000 000	9,000,000
Specific extension	0·00000008	0·00000011
Coefficient of expansion ...	0 0000093	0·0000130
Extension in feet for full working stress	116	118
	100-ft. span 0·096	0·066
	200-ft. span 0·192	0·132
	400-ft. span 0·384	0·264

It should be noted that the physical constants are such as apply to stranded cables in both cases, all schemes transmitting appreciable quantities of energy now using stranded conductors. This is more than usually true in this country, where it is doubtful if legislation will permit of the use of such high line voltages as render the use of a small solid conductor preferable to the equivalent stranded cable.

Before leaving the question of fundamental properties it should be mentioned that now that such large quantities of high-grade aluminium are being produced for electrical work, the conductivity and tensile strength can be confidently guaranteed. Conductivity and freedom from corrosion are equally dependent on the purity of the metal, and improvements in production have rendered it possible to place upon the market aluminium of well over 99 per cent. purity.

The enormous outlay called for by the line conductors of a transmission scheme renders the economic question a vital one, and before a comparison such as this is justifiable the competing metal must show an advantage over copper in respect of capital invested.

According to the prices ruling at the end of 1911, the comparative figures were :—

	£
Copper wire (per ton)	71
Aluminium wire (half ton)...	40
Saving in favour of aluminium	£31

This computation of course, takes into account the fact that aluminium is for a given conductivity exactly half the weight of copper. The extra charges for drawing and stranding are a function of the length of the cable, hence on a mileage basis are approximately equal for both metals. The saving as calculated on the above basis is therefore unaffected except where multi-stranded cables of small diameter wire are employed.

Turning to the technical problems involved, a starting-point is fixed by the Board of Trade recommendations for overhead line construction. Briefly stated, these call for a stress in the conductor not exceeding one-fifth of the ultimate tensile strength, assuming a temperature of 22° F., and a horizontal wind-pressure of 30 lbs. per square foot (corresponding to 18 lbs. per square foot on the projected surface of the wire). These values, together with certain of the physical constants already set forth, can by suitable manipulation be substituted in the standard equation for deflection and stress where—

$$\text{Deflection at mid-span} = \frac{W\,l^2}{8\,a\,S},$$

and in which—

W = loading per foot run (lbs.).
l = span in feet.
a = cross-section of conductor (square inches).
S = maximum working stress (lbs. per square inch).

The loading on the wire (W) is the resultant of its weight and the wind pressure—

$$W = \sqrt{w^2 + p^2};$$

and the inclination of the plane in which the conductor will hang is given by—

$$\text{Angle with vertical } \theta = \tan^{-1}\frac{p}{w},$$

the two forces p and w acting at right angles. The loading (W) is shown by the curves in Fig. 1, in which both of the components and the resultant have been plotted as a function of the cable diameter. The enormous preponderance of wind over weight loading in the

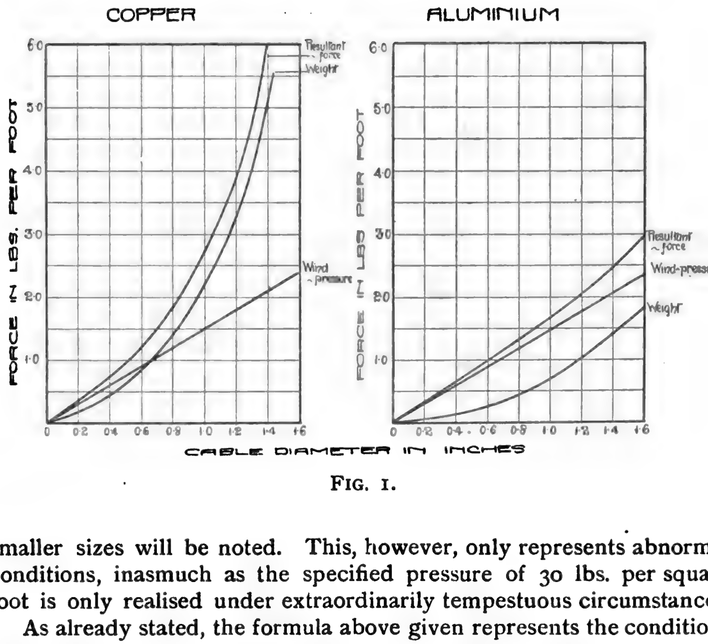


FIG. 1.

smaller sizes will be noted. This, however, only represents abnormal conditions, inasmuch as the specified pressure of 30 lbs. per square foot is only realised under extraordinarily tempestuous circumstances.

As already stated, the formula above given represents the conditions obtaining at minimum temperature, 22° F. With increase of temperature the factor of linear expansion will come into play and the deflection will increase. It is highly important to know the value of the maximum deflection under conditions of high summer temperature in order that the minimum distance of the line above ground-level may be observed, and the height of the poles chosen in accordance therewith.

It will readily be seen that as the cable expands with increased temperature the stress is relieved. This reduction of stress, however, gives a diminution of strain, and the conductor will therefore extend due to temperature rise an amount which is *less* than that calculated by

the shortening due to reduction of stress. From the other standpoint it will be seen that the temperature rise for a given deflection will be *greater* than that worked from the ordinary formulæ. The necessary correction may therefore most conveniently take the form of an increment to the calculated temperature rise. The correction used by the author is a modification of that suggested by Mr. Shields in the discussion on a paper by Burne on "Overhead Construction." *

In predetermining the forces acting on the conductors at the lower temperature limit of 22° F. it is necessary to take into account the wind-pressure. In calculating the maximum deflection due to the highest summer temperature, however, wind-pressure must be eliminated. Apart from the physical impossibility of a hurricane at 100° F., it is necessary to calculate the maximum deflection in a *vertical* direction in order to estimate the necessary height of pole or other supporting structure; in other words, the deflection in still air is what is required. Some manipulation is necessary to allow for this change in the conditions, and the author has found it convenient to use a graphical method for effecting this.

The conditions obtaining at 22° F., as has been seen, are expressed by—

$$\delta = \frac{W\, l^2}{8\, a\, S}.$$

It will be noted that all save δ and S are constant, hence—

$$\delta = \frac{K}{S} \text{ and } \delta S = K.$$

If now the wind-pressure disappears the state of affairs is given by—

$$\delta_1 = \frac{w\, l^2}{8\, a\, S}$$

i.e.—

$$\delta_1 = \frac{K_1}{S_1}.$$

Ample information is available for the estimating of K and K_1; the the latter being obtained, a locus is fixed for—

$$\delta_1 = \frac{K_1}{S_1}.$$

This curve plotted for a 200-ft. span in aluminium is shown in Fig. 2, whilst at the top of the diagram is the elastic extension curve plotted downwards to represent a contraction. This is obtained simply by multiplying the stress by the elastic constant and by the length of the span. The variation of deflection with extension of the cable is calculated from the equation already given :—

$$L = l + \frac{8\, \delta^2}{3\, l};$$

* *Journal of the Institution of Electrical Engineers*, vol. 31, p. 432.

hence a series of deflection curves can be plotted from the values in the elastic extension curve. The points where these lines intersect the δ_1 S_1 hyperbola show the positions where the catenary and elastic laws coincide and give the actual deflections which the conductor will take up, with the corresponding stresses.

The respective deflections on the copper and alumium cables with and without wind-pressure are shown in Fig. 3. These curves

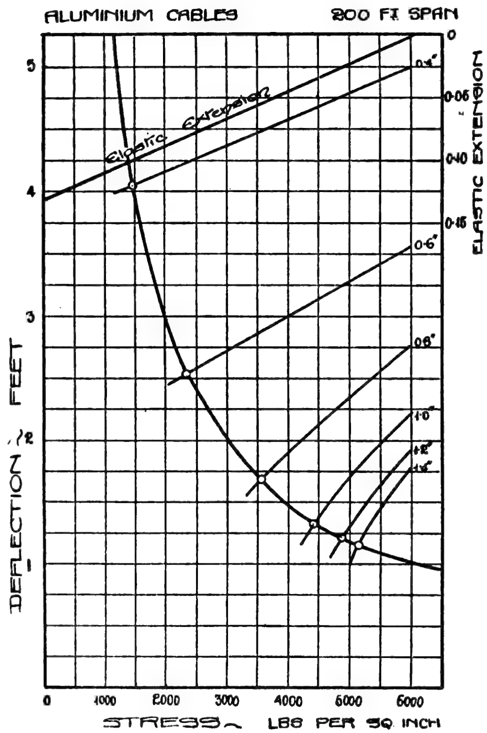


FIG. 2.

summarise all the foregoing calculations. It will be seen that the maximum amount by which the deflection on an aluminium line exceeds that for copper is about 35 per cent. With smaller sizes of cable than 0·1 sq. in. of course this ratio will increase, but this illustrates the fallacy of the statement frequently made to the effect that aluminium is only suitable for small and unimportant transmission schemes. It is exactly for the larger power lay outs that the advantages are best shown, and the greater the amount of power transmitted, the better become both the technical and economical features of aluminium. The only point open to question is, at what section of cable does

aluminium become superior to copper? The present investigation is carried down to a section of approximately $\frac{1}{10}$ sq. in., or 100-amperes

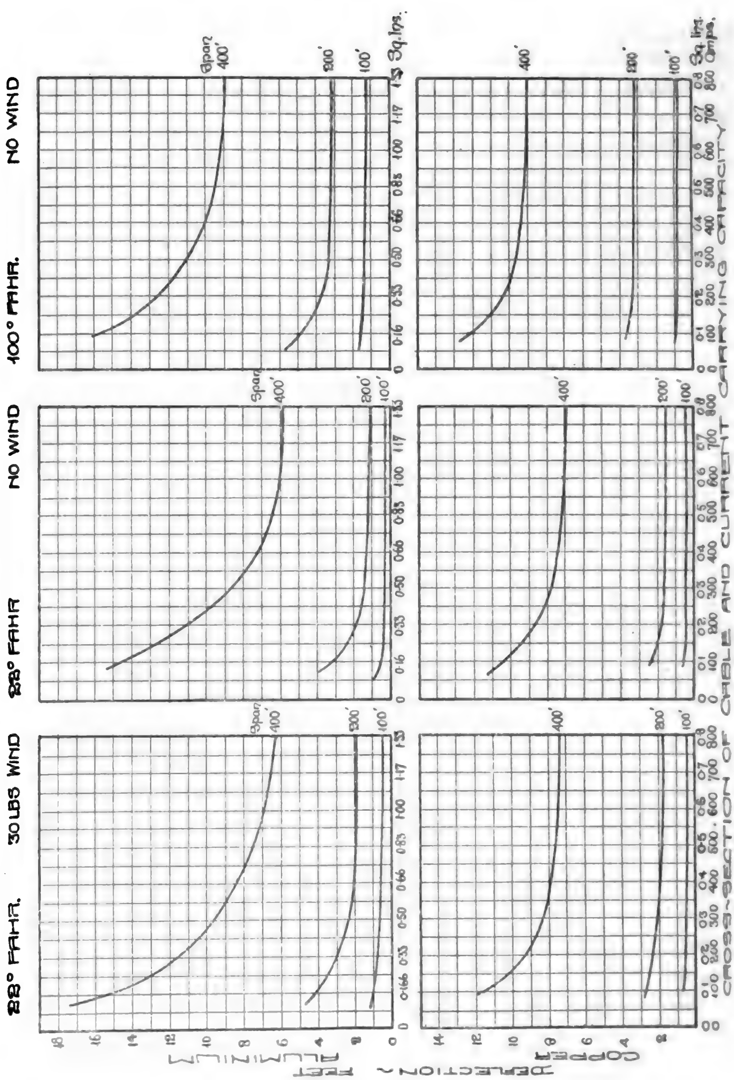


FIG. 3.

carrying capacity in copper, and it does not seem that the least disadvantage accrues from the replacement of copper by aluminium.

In dealing with power transmission at the present day, however,

there is a far more valid objection to small section conductors than the matter of deflection, and that is the phenomenon of corona. It

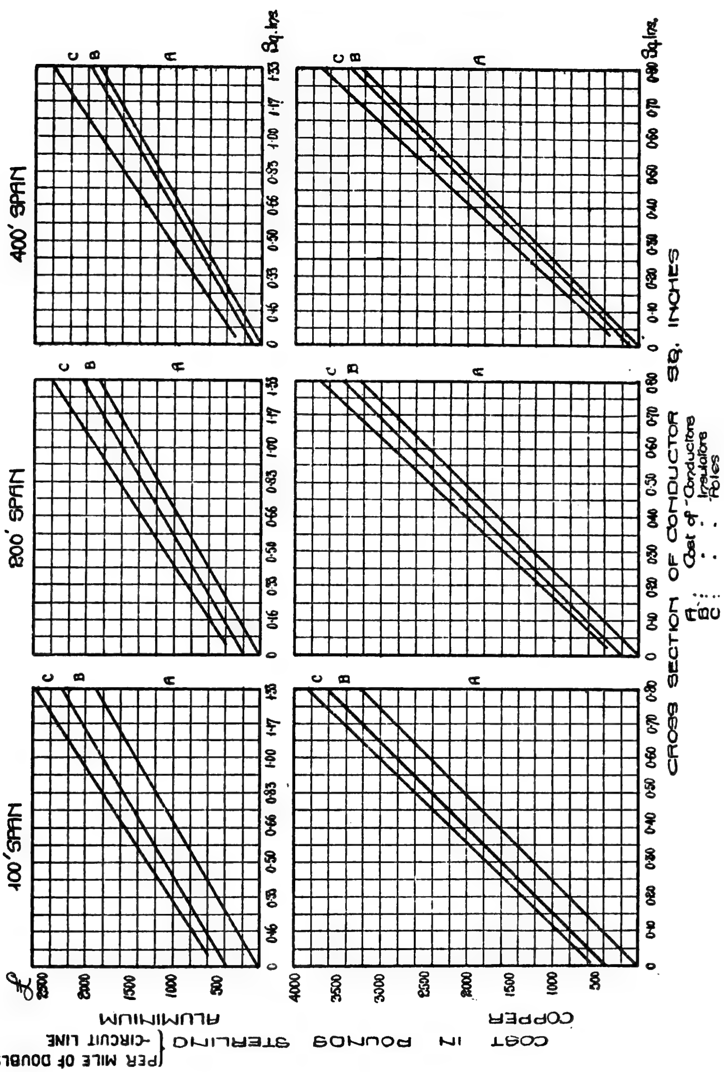


FIG. 4.

has long been known that high-transmission pressures occasion a loss due to brush discharge from the conductors.

The feature which has been brought out most strongly is the rapid augmentation of corona loss with a reduction in the size of the

conductor. At working pressures of 80,000 volts and over, this difficulty is a very real one, and although such high working pressures are by no means imminent for British transmission schemes, it should be remembered that in our climate corona will form at an appreciably lower voltage than in the drier atmospheric conditions obtaining on the American continent. The fact that the larger diameter conductor will carry a given pressure with a lower corona loss is the main reason which dictated the exclusive use of aluminium on the transmission system of the Ontario Commission which operates at 110,000 volts.

The cost diagrams (Fig. 4) represent the cost per mile of material for a high-pressure double-circuit 3-phase line, comprising metal, poles, and insulators. Analysis of these curves will show that in no case does the extra cost for the poles on the aluminium lines approach the value of the saving effected on the line conductors. This is a most important result as it refutes the statement often made that a saving on the cost of line conductors does not imply a saving on the whole expenditure.

Much of the information relative to the use of aluminium is here published for the first time, and the author's best thanks are due to Mr. Arthur Jacob of the British Aluminium Company, Ltd., for permission to use the same.

ELECTRICAL WORKING OF AUXILIARY MACHINERY ON MODERN STEAMSHIPS.

By E. T. CAPARN, Associate Member.

(*Abstract of paper read before the* GLASGOW STUDENTS' SECTION, *15th March*, 1912.)

In considering the framework of a paper of this description it is necessary as a preliminary measure definitely to limit the range to be covered in a naturally extensive subject; therefore the author has confined the discussion to comparisons of steam and electrical working only, and to machinery which is strictly auxiliary, for the purposes of the Mercantile Marine, excluding vessels of war entirely.

It must also be understood that the problem is only worth consideration for vessels of high class possessing a varied and extensive equipment of auxiliary machinery. For the purpose of this paper, selection has been made of a generally favoured class of vessel, of length about 550 ft., beam 65 ft., displacement 18,000 tons, carrying passengers, cargo, and probably mails. The driving of the auxiliary machinery has been dealt with in three stages—utilisation, transmission, and generation of the power agent, the suitability and relative efficiency of the individual items being considered under the first heading.

Utilisation.—In Schedule I. is given a list of the auxiliary machinery required for a vessel such as that described, and detailed consideration of the items follows:—

Items 1, 2, and 3 comprise machinery whose functions are directly connected with the working of the propelling engines; they are situated in close proximity to the main steam supply, and steam working by direct duplex pumps is the most suitable method, so that further consideration of them is unnecessary.

Items 4, 5, 6, 7, and 8 are all low-pressure pumps with somewhat similar duties, so that the same type of pump, though of varying size, may be used for the whole group.

The two types generally favoured, and therefore selected for comparison here, are the simplex or duplex direct steam pump, and the motor-driven high-lift centrifugal pump with one or more discs, and in Schedule II. is given a comparison of the working efficiency of two complete sets of pumps. The figures given are taken direct from actual recent examples, and consistently indicate about 30 per cent. economy of consumption in the motor-driven type. No allowance has

been made for transmission losses, which are dealt with later, but the dynamo overall efficiency is included, since the steam consumption of the motor pump is obtained *pro rata* from the ¾ load consumption of the dynamo engine.

Schedule I.

List of Auxiliary Machinery to be Discussed (excluding Dynamo Engines).

1. Boiler feed pumps, one for each main boiler with interconnections.
2. Evaporator and auxiliary feed pumps, about three in number.
3. Condenser circulating pumps.
4. Ballast and ejector pumps ...
5. Bilge pumps ... ...
6. General service pumps ...
7. Sanitary and salt water service pumps... ... ...

   (Items 4–7:) Usually interconnected and alternatively available, with connections to fire mains.
8. Fresh water pumps.
9. Fans for boiler-room forced draught.
10. Fans of small size for general ship ventilation.
11. Windlass and warping capstans.
12. Deck winches for boat and cargo working.
13. Steering gear.
14. Refrigerating plant.

In addition to these a ship of the type considered will contain probably a passenger elevator, a stores hoist, and several small motors in the galleys, laundries, and stores.

Item 9.—The power required for these fans, without differentiation of the system of forced draught employed, may be regarded roughly as 1 per cent. of the power of the main engines, *i.e.*, 100 H.P. in the case of 10,000-H.P. engines, divided into units of about 20 H.P. each. The steam fan is coupled direct to a single-cylinder enclosed engine, and as the heavy fan provides suitable flywheel effect, makers are able to obtain a consumption figure as low as 31 lbs. per 1-H.P.-hour. In the case of the motor-driven fan the power required comprises a large fraction of the dynamo load, and, as the working time factor at sea is 100 per cent., the consumption may be as low as 28 lbs. per motor B.H.P.-hour. The motor employed is usually series wound with series-parallel control, so that the regulation of the speed is simple and definite, a matter of considerable importance with the modern systems of trunked draught. Lubrication and attendance costs of the motor-driven fan are lower, and transmission losses are negligible since the fans are situated in or immediately over the boiler-rooms and near to the dynamos.

Item 10.—The small motor-driven fan has so many recognised advantages over other kinds that the only open question concerns the type of motor to be employed. The size of the fan, of the cased centri-

SCHEDULE II.

Comparison between Steam and Electrical Working of a Typical Equipment of Low-pressure Pumps.

Purpose.	Pump.			Steam Cylinders.			Direct-current Motor.					
	Capacity. Ton-hour.	Water-head. Feet.	Water-power.	Dimensions.	Speed Strokes.	Steam Used. Lbs. per Hour.	Motor Efficiency.	Pump Efficiency.	Over-all. Efficiency.	Speed.	Motor Horse-power.	Steam Used. Lbs. per Hour.
				Inches.								
Two general service pumps (includes ballast and ejector duties)	200	100	22·40	Duplex * 10 × 12	130	1,705	0·86	0·650	0·555	1,050	40·40	1,200
Two bilge pumps	90	50	5·10	* 6 × 8	270	429	*† 0·85	0·610	0·520	140	9·80	292
Three sanitary pumps	80	70	6·34	7 × 7	278	494	* 0·85	0·614	0·522	1,270	12·10	360
One fresh-water pump	20	70	1·57	4½ × 3½	296	135	* 0·82	0·450	0·369	1,600	3·49	104
One fire pump ...	60	100	6·78	* 7 × 8½	224	510	0·84	0·620	0·520	1,200	13·00	388

* These figures relate to pumps actually installed in a recently completed vessel.

† These figures refer to a double helical-geared three-throw plunger pump, and not to a centrifugal pump.

fugal type, always falls between $7\frac{1}{2}$ and 20 in. diameter, and the power of the motor between $\frac{1}{2}$ and $3\frac{1}{2}$ H.P., and for these units the simple series motor with series-parallel control is much the cheapest arrangement, and is quite satisfactory in practice.

Item 11.—Economical working of capstan machinery is not important, as the working time factor is extremely low. The essential consideration affecting the design of the forward windlass is the widely fluctuating nature of the load when heaving the anchor, the fluctuation depending on the ground-hold and the periodic motion of the ship. These fluctuations must be met by prompt changes of speed on the part of the capstan, and the design of the gear must be such that, while the components possess stiffness, and therefore weight, the speed is kept low, and the stored energy at a minimum.

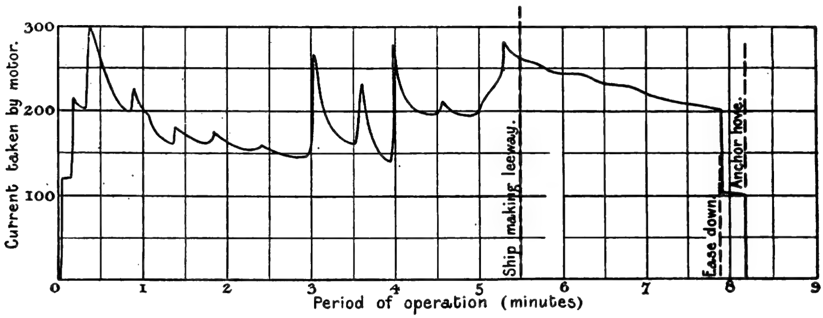


FIG. 1.—Electric Capstan.

Curve taken from Series Motor No. 8763, 120 H.P., 6 poles, 210 volts, heaving 50 fathoms of cable and anchor.

Total weight lifted	... ...	$10\frac{1}{4}$ tons.
Speed (maximum)	... ...	40 ft. per minute.

With a steam-driven gear the fulfilment of these conditions is comparatively easy by making the cylinders large and the piston speed low, but with a motor-driven gear it is difficult to keep down the stored energy in the components, and when this is done there is the disadvantage that the torque fluctuations are transmitted direct back to the main dynamo engines.

Fig. 1 shows a current-consumption chart obtained from an experimental motor-gear some years ago. Numerous designs have been tested, but it cannot be said that experience so far has justified the additional first cost.

As regards the smaller warping capstan the conditions are not so exceptional, and a series motor driving the warping drum through short-pitch worm-gearing is entirely suitable.

Item 12.—Reliability is an essential qualification of these winches, which are mainly required when the ship is in harbour, during which period they are roughly handled with a working time factor of possibly 50 per cent.; they are distributed on the decks in the neighbourhood

of cargo hatches, and their distance from the boilers is considerable. An equipment of eight single drum winches, each capable of 2 tons at 160 ft. per minute, is assumed, and Schedule III. furnishes a comparison of working efficiencies under steam and electric driving, the figures being worked out from actual recent examples. The motor winches show a saving of 40 per cent. at an average three-quarter load, disregarding at present the loss in the steam pipes.

SCHEDULE III.

Comparison of Steam and Electrical Working of a Typical Equipment of Cargo Winches.

	7 in. × 12 in. Steam Winch.		30-H.P. Motor Winch.	
	Full Load.	¾ Load.	Full Load.	¾ Load.
Weight raised by rope (cwt.)	40	27	40	27
Velocity of rope (feet per minute) ...	160	184	160	184
Rope horse-power	21·3	16·5	21·3	16·5
Efficiency of gearing *	0·65	0·63	0·70	0·68
I.H P. of steam cylinders	32·7	26·1	—	—
Crankshaft revolutions	150	172·5	—	—
Lbs. of steam per foot-ton	0·070	0·078	—	—
Motor efficiency	—	—	0·86	0·82
Overall efficiency (motor and gear) ...	—	—	0·602	0·56
Input horse-power to motor	—	—	35·4	29·5
Lbs. of steam per foot-ton	—	—	0·044	0·0474
Intermittency factor	25/115	25/115	25/115	25/115
Lbs. of steam per winch per 24 hours	7,100	6,120	4,450	3,730
Lbs. of coal per winch per 24 hours ...	747	645	468	393
Saving (8 winches) tons of coal per 24 hours...	—	—	0·996	0·902
Weight of winch complete	3 tons 8 cwt.	—	3 tons 14 cwt.	—

* Includes losses in valves and link motion.

Steam Winch.—2 cylinders, 7 in. × 12 in.; steam at 120 lbs. square inch; crankshaft, 300 revolutions; double helical gear driving winding drum 18 in. diameter.

Motor Winch.—30-H.P. motor at 700 revs. with two-thread worm, gearing into cast-iron wormwheel with 44 teeth; winding drum, 18 in. diameter.

Brakes.—Solenoid operated brake on motor shaft, a foot brake on the slow-speed shaft.

Controller.—Drum type; 6 hoisting steps; 3 power steps lowering, and 3 steps of dynamic braking.

Item 13.—Reliability, accuracy, and promptness are the primary conditions to be fulfilled in the design of a steering equipment, and only subordinately comes the condition of economical working, but this is worth attention in view of the high working time factor at sea.

The requirement of reliability is amply fulfilled by the ordinary steam-gear, but on the other points electric driving can show distinct advantages. Of the various motor-gears which have been designed

SCHEDULE IV.—*List of Auxiliary Machinery suitable for a First-class Passenger and Cargo Vessel.*

550 ft. length; 65 ft. beam; displacement, 18,000 tons; pressure, 100 volts.

Items.	Dimensions of each Unit.	Number Installed.	Type of Machine Employed.	Power of Motor or Size of Engine.	Steam Consumption. Lbs. per Hour.	Maximum Demand. Amperes.	Amperes Load. Ship in Harbour.	Amperes Load. Ship at Sea.
General service, fire, and ballast pump ...	200 tons at 150 ft.	1	3-stage centrifugal pump, compound-wound motor	36 B.H.P.	1,200	375·0	375	375
General service, fire, and ballast pump ...	200 tons at 150 ft.	1	Direct duplex steam pump	10 in. × 12 in.	1,705	—	—	—
Bilge pumps	90 tons at 50 ft.	2	Centrifugal pump, compound-wound motor ...	8½ B.H.P.	292	91·3	91	91
Fresh-water pumps...	20 tons at 70 ft.	1	Centrifugal pump, compound-wound motor ...	3 B.H.P.	104	32·5	—	32
Sanitary pumps ...	80 tons at 70 ft.	3	Centrifugal pump, compound-wound motor ...	10½ B.H.P.	720	225·0	225	112
Fire pumps	60 tons at 100 ft.	1	Direct simplex steam pump	7 in. × 8½ in.	510	—	—	—
Fans for boiler-room forced draught ...	20 B.H.P.	4	Cased bladed fan and series-wound motor ...	20 B.H.P.	1,120	350·0	—	350
Fans for general ship ventilation	15 lbs. centrifugal	16	Cased fan and series-wound motor	2 B.H.P.	720	225·0	112	225
Windlass, main forward	20 tons at 60 ft.	1	Non-compound 2-cylinder 14 in. × 15 in. geared...	14 in. × 15 in.	69 per minute	—	—	—
Capstan, warping aft...	10 tons at 30 ft.	2	Worm and spur-geared series-wound motor ...	34 B.H.P.	26 per minute	300·0	—	—
Cargo and deck winches	2 tons at 160 ft.	8	Worm-geared series-wound motor	30 B.H.P.	111	1,040·0	350	—
Steering gear... ...	250 ft.-tons torque	1	Hastie's patent electro-hydraulic gear	45 B.H.P.	200	400·0	—	63
Refrigerating machinery	320,000 B.T.U.	2	Dry air at 110 lbs. per sq. in.; geared compound motor	70 B.H.P.	1,970	615·0	615	615
Passenger elevator ...	6 cwt. at 140 ft.	1	Worm-geared shunt-wound motors	5·7 B.H.P.	—	50·0		
Stores hoist	10 cwt. at 80 ft.	1	Worm-geared shunt-wound motors	5·6 B.H.P.	—	50·0	150	150
Laundry machinery ...	—	3	Shunt-wound motors ...	3·0 B.H.P.	—	78·0		
Galley machinery ...	—	4	Shunt-wound motors ...	3·0 B.H.P.	—	78·0		
—	—	—	—	—	—	—	1,918	2,013
				Lighting load			360	840
				Heating load			—	100
				Total (kilowatts) ...			227·8	295·3

only those which comprise a continuously running motor can claim to have survived the test of practical experience.

The author had recent experience with one such gear fitted on the T.S.S. *Orama*, built at Clydebank for the Orient Company, and very successful results were obtained. The equipment, of the electro-hydraulic type devised by Dr. H. S. Hele-Shaw and F. L. Martineau, and manufactured by Messrs. J. H. Hastie & Co., showed an average consumption on a comparatively straight steering course of only 470 watts, equivalent to 150 lbs. of steam per hour at the dynamo, which quantity would be consumed in the 11 in. × 10 in. companion steam-gear with which the vessel is fitted in about 267 revolutions of the crankshaft. The average movement of the engine per hour is probably three times this figure, so that a saving of 300 lbs. of steam per

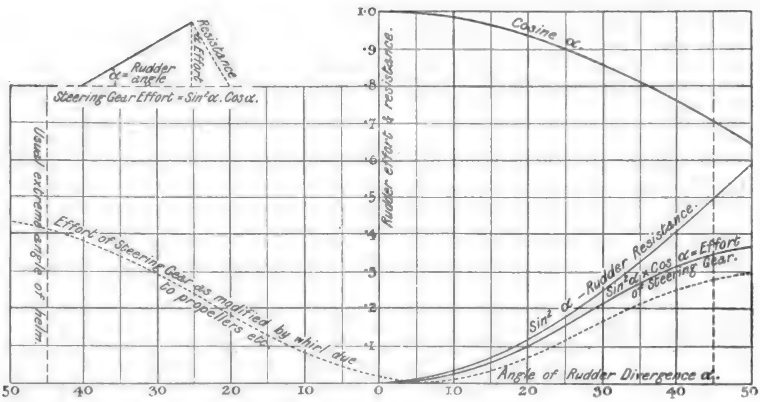


FIG. 2.—Curves showing Theorectical Rudder Resistance and Effort at constant Ship Speed.

hour is effected without any allowance made for loss in the great length of supply steam pipes.

The steering gear and the arrangements for power supply must be designed to sustain heavy overloads for short periods in heavy weather, or for emergency turning, and Fig. No. 2 shows the general form of the law connecting the rudder resistance R as a function of the angle of divergence α. Theoretically R should be proportional to $\sin^2\alpha$, and to (speed of ship)^3, but in practice propeller whirls and other water movements modify the conditions considerably.

Item 14.—In a modern vessel the working time factor of the refrigerating machinery is sometimes 80 per cent., and the power required considerable. The small auxiliary pumps and fans are particularly suitable for working electrically, but the conditions for electrically driving the main compressors are not so favourable. The compression

in the cylinders of ammonia or carbonic acid plants is high and the crankshaft speed low, so that reduction gearing and flywheel effect are necessary between the motor and compressor, and the motor must be compound wound to minimise the fluctuation in demand on the ship's power supply. The peak of compression in the dry-air system is much lower and the conditions more favourable for the motor drive.

For the vessel under consideration two equipments are required, each capable of 20 tons refrigeration with water at 60° F., and the

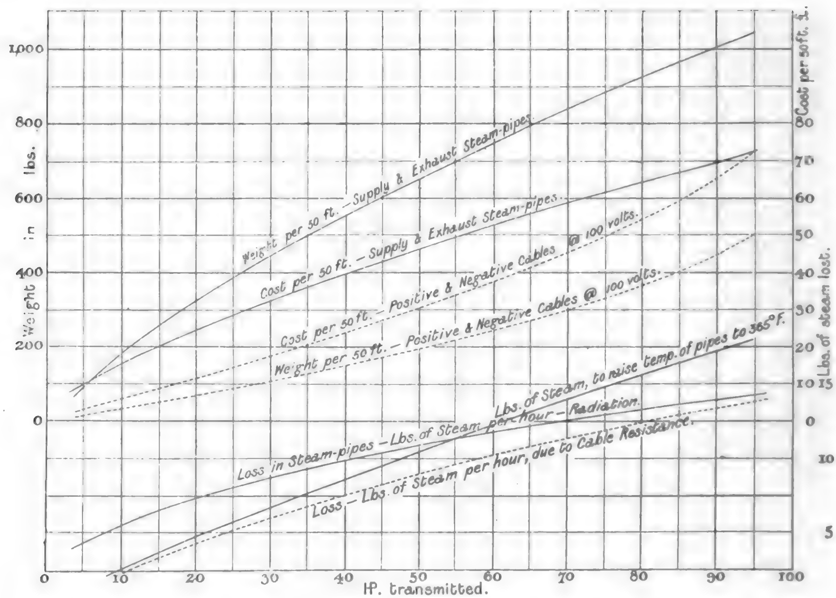


FIG. 3.—Curves showing Comparative Data of Steam Pipes and Insulated Cables.

The following assumptions are made in estimating the radiation :—

Mean atmospheric temperature = 65° F.
Temperature of steam at 150 lbs. per square inch = 365°.
Heat units lost per square foot of lagged surface = 180 B.Th.U.

power may be arrived at by estimating approximately 3½-B.H.P. motor, or 3½-I.H.P. steam per ton of refrigeration per 24 hours. The steam-driven plant is usually compound, requiring about 30 lbs. per I.H.P.-hour, as against 33½ lbs. per B.H.P.-hour for the motor-driven equipment.

The motor drive cannot therefore claim economy except as regards transmission losses, but important advantages are obtained through the steadier working of the plant, since variations in the boiler pressure do not affect the supply voltage, and the cost of attendance and lubrication is considerably lower.

Discussion of the miscellaneous items in Schedule I. is unnecessary, as the motor drive is generally recognised as the best method available for small and scattered units of machinery.

The consideration of the various items individually having been completed, Schedule IV. gives, for the vessel under discussion, a complete list of the auxiliary machinery as constituted therefrom, the power demand on the dynamos, which is referred to elsewhere, being also indicated.

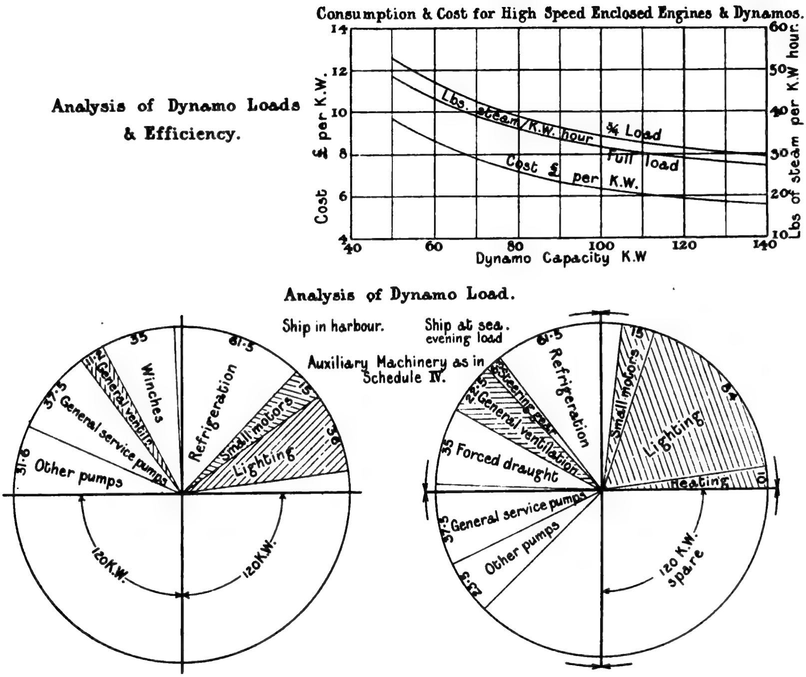


FIG. 4.

Transmission.—In dealing with the transmission efficiency of the two systems, only approximate comparisons are possible ; conditions and practice differ considerably, and there are, in fact, too many independent variables. The comparative curves in Fig. 3, for lagged steam pipes and insulated cables, have, however, been compiled from a fair average of recent practice, the loading of the cables being based on the recently superseded Institution Wiring Rules, and the rating of the steam pipes assumed on a steam velocity varying from 2,000–2,500 ft. per minute, over the range of diameters shown, at a working pressure of 150 lbs. per square inch.

The curves show clearly the economy effected by electrical transmission, the saving being proportionally greater for the smaller units

of power transmitted, and in this connection it must be remembered that the majority of the items constituting the auxiliary machinery fall between the limits of 3 and 50 H.P.

Generating Machinery.—In this section has been considered the effect of smaller or greater power demand on the dimensions and efficiency of the dynamos. The type of vessel dealt with is lighted by about 2,000 lamps of 60 watts consumption, and of this total 30 per cent. may be regarded as day load, and 70 per cent. as evening load, the former figure serving also for the period when the ship is in harbour. The circular charts on Fig. 4 furnish an analysis of the dynamo load when the auxiliary machinery is constituted as in Schedule IV. and the lighting load as stated, and show the necessary dynamo capacity to be 480 k.w. in 4 units of 120 k.w. each. If, however, the auxiliary machinery were constituted with the least possible electrical apparatus, namely, small motors and general ventilation, the maximum load would be 132 k.w., as shown shaded in the charts, and the dynamo provision would be 225 k.w., in 3 units of 75 k.w. each. For convenience of calculation it has been assumed that the dynamos work at a mean ¾ load continuously, and the curves given on Fig. 4 connect consumption, cost, and output for modern high-speed engines. These curves show that a saving of 8 lbs. of steam per kilowatt-hour is effected by the use of the larger dynamos, representing on lighting and small motors alone a saving of approximately 1,056 lbs. per hour on evening load, and 670 lbs. per hour on day load, a total of 18,386 lbs. per 24 hours, equivalent to, roughly, £150 per annum reduction of fuel costs.

All the stages between the boilers and the auxiliary machinery having been dealt with, the author's conclusions may be summarised as follows:—

With the exception of a few special items, all the auxiliary machinery can be electrically driven with a higher mechanical efficiency than can be shown for steam working; the transmission system is more efficient, more convenient, and cheaper as regards first cost and subsequent upkeep.

The objection commonly advanced to a large electrical equipment, namely, the necessity of greater dynamo provision, is negatived, since it can be shown that the use of larger dynamo units, having a lower steam consumption per unit generated, and the possibility of a higher load factor, results in a saving, on the lighting and small motor load alone, sufficient to pay interest and replacement charges on the additional dynamo expenditure, regardless of a corresponding economy in the rest of the system.

Only one type of ship has been treated in detail, but the results are generally applicable. The factors in favour of electrical working remain positive until a type of vessel is reached in which the auxiliary machinery has become so reduced as regards variety of purpose, or so concentrated as regards the size of the unit, that the load factor on the generating plant is reduced below the limit of economical working.

A direct-current system of 100 volts has been assumed throughout this paper as being most suitable for the conditions encountered, though in several very large ships and in vessels where large motor units are required, a pressure of 210 volts has been adopted to keep down the weight of the distributing cables.

In any case the efficiency of the electrical distribution is improved by the increase of voltage, so that the main contention of the paper holds good.

HIGH-VOLTAGE TESTING TRANSFORMERS (100,000–750,000 VOLTS).

By R. G. PARROTT, Student.

(*Abstract of paper read before the* MANCHESTER STUDENTS' SECTION, *5th March*, 1912.)

The object of this paper is to discuss certain theoretical and practical features relating more especially to the design and construction of high-voltage testing transformers of a normal voltage above 100,000.

Electrical Characteristics. — In considering the most important electrical characteristics, the aim should be to use as large a sectional area of iron, and as few turns in the winding as possible, together with sufficient additional insulation between the end-turns of the high-tension winding to enable it to withstand the high-frequency oscillations which are invariably present during most switching operations, short circuits, etc. Owing to the increased volts per turn, brought about by the use of a larger sectional area of iron, the number of turns will be reduced. The copper factor will therefore be higher, and the windings will not only be easier to insulate and cheaper to wind, but will be stronger mechanically with less chances of open circuits occurring. Again, the reactance, which is proportional to the square of the number of turns, will be reduced—a desirable feature where extreme accuracy of ratio is required. The value of the volts per turn has, during the past ten years, risen from approximately 3–4 to 15–25.

Output.—In the majority of cases where the transformer is only required for testing small samples of insulation, the output in kilovolt-amperes will be very small, but with cables, transmission lines, large electrical plant, etc., the necessary output, since each acts as a condenser, will be much greater on account of the larger magnetising current taken by such apparatus. Since the output of the testing transformer depends on the static capacity of apparatus to be tested, an approximate idea of the necessary kilovolt-amperes required for any particular apparatus may be obtained from the following formula, which is based on the flow of current to a condenser where a sine wave of E.M.F. is applied to its terminals.

$$\text{K.V.A.} = \text{I E } 10^{-3} = 2 \, . \, \pi \, . \sim . \, \text{C E}^2 \times 10^{-9},$$

where I = current in testing transformer $\sim$ = frequency in cycles per second, C = capacity of apparatus under test in microfarads, and E = test voltage.

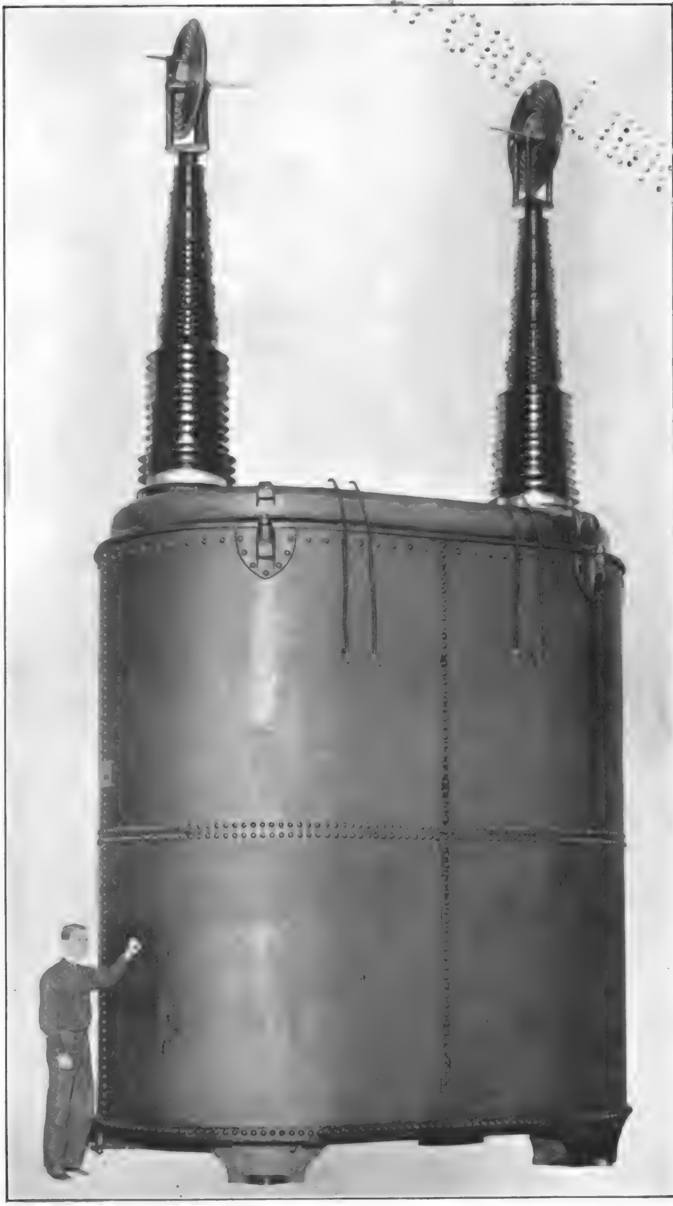


FIG. 1.—750,000-volt Testing Transformer.

It has therefore become general practice to provide a transformer having sufficient output to allow of a practical type of construction being adopted, and to be able to supply the charging current and leakage current, as well as the energy absorbed by dielectric hysteresis, and having also a minimum impedance drop on short circuit. The size of the transformer, apart from the kilovolt-amperes output, will be largely influenced by the over-potential and flash tests guaranteed.

Temperature Rise.—Owing to the fact that the majority of testing transformers are rarely used continuously, it is not necessary to rate them on the basis of temperature rise after continuous full-load run, but it should be sufficient to rate them on the basis of the maximum current the transformer could deliver for short periods. The actual temperature of the insulation should always be kept below 90 to 95° C., otherwise its properties will very soon be destroyed. For this reason, and because of the comparatively large quantity of insulation, it is advisable to rate the copper at a fairly low density, approximate 800 amperes per square inch, and provide cooling ducts where the insulation is likely to become bulky.

Design of Tanks.—Since the watts per cubic foot of active material are low, and the necessary clearances to prevent flashing over between the windings and inside of tank are comparatively large, a plain tank gives sufficient radiating surface to keep the temperature at a safe value. This is demonstrated by the fact that more than 90 per cent. of the testing transformers are immersed in plain boiler iron tanks with either welded or riveted joints. A typical design is shown in Fig. 1, which illustrates a 500-k.v.a. 750,000-volt, 60-period testing transformer built by the General Electric Company, Schenectady, U.S.A. The dimensions are 8 ft. × 13 ft. × 15½ ft. high, and 28 ft. to the top of the terminal.

Relative Advantages and Disadvantages of the Shell and Core Type for High Voltages.—For comparatively low voltages there is little to choose between the two types, but for the higher voltages it becomes perfectly obvious, after a little consideration, that the core type is the only practical solution as regards both construction and cost.

The author is of the opinion that for voltages above 50,000 the core type should be adopted, although some manufacturers can balance the cost at approximately double this value. Considering the question first of all from the manufacturer's point of view, with special reference to the mechanical construction, one will see that the coils of the shell type, having a greater mean turn, are much more likely to suffer damage from bending and twisting due to their increased flexibility and difficulty in handling than the more rigid circular core type coils of much smaller dimensions.

The actual quantity of insulating material is larger and more awkward and expensive to handle than that required on the core type. The time required for completely assembling a core type transformer is less than that required for a shell type.

From the operating engineer's point of view—with reference to

breakdowns—it is easy to see that a high-tension coil can be replaced in a very much shorter time in the case of the core type than in the case of the shell type, where all the iron has to be dismantled before the coils can be separated.

Insulating Materials.—The insulation of the windings is of course the most important feature to be considered where high voltages are present. Far better results are to be obtained by the proper selection and mechanical disposition of the insulation than by simply relying on a sufficient quantity of such material.

Parts to be insulated from each other should be designed to have approximately uniform electrostatic capacities, so that the insulation may be under uniform electric stress and free from high potential differences due to condenser effect.

Fibrous materials alone should not be relied on except for mechanical protection, since their dielectric properties are not good unless thoroughly treated with compounds, gums, varnishes, etc., which are far more durable. Mineral oil is one of the very best insulating materials, and is invariably used to much advantage with all high-voltage transformers. In addition to its good dielectric properties, it effectively protects the windings from moisture and is a good cooling medium.

Arrangement and Construction of Winding.—There seems to be no standard practice with regard to the grounding of either the end or the middle point of the high-tension winding. Some firms build all their testing transformers with one side permanently grounded to the core. This seems good practice since it meets practically all conditions of test. The effect of grounding will be to reduce the dimensions and cost of the transformer. The smaller the output and the higher the voltage, the greater will be this reduction in cost.

There are many ways of connecting the high-tension coils, but the two most commonly in use are—firstly, the connection of all coils in series, starting at the top of one leg and finishing at the top of the next—this gives the maximum voltage difference between the top coil of each leg (see Fig. 2 which shows the windings of the 750,000-volt transformer shown in Fig. 1). Secondly, the coils of both legs are cross-connected all the way up from the bottom to the top of the legs. With this arrangement there is very little voltage difference between coils on different legs in the same plane.

An extremely interesting and novel type of construction is illustrated in Fig. 3—it shows the windings of a 500,000-volt testing transformer built by the Westinghouse Company, Pittsburg Pa, U.S.A. The coils connected are as follows : The bottom coil on the left-hand leg has one end grounded and the other end connected to the bottom right-hand coil, which is again connected to the top right-hand coil by a connection which passes through the innermost micarta tube. This top coil is then cross-connected to the top left-hand coil (not shown), which is connected through the inner micarta tube to the second from the bottom on the same leg, and so on until finally the high-voltage end

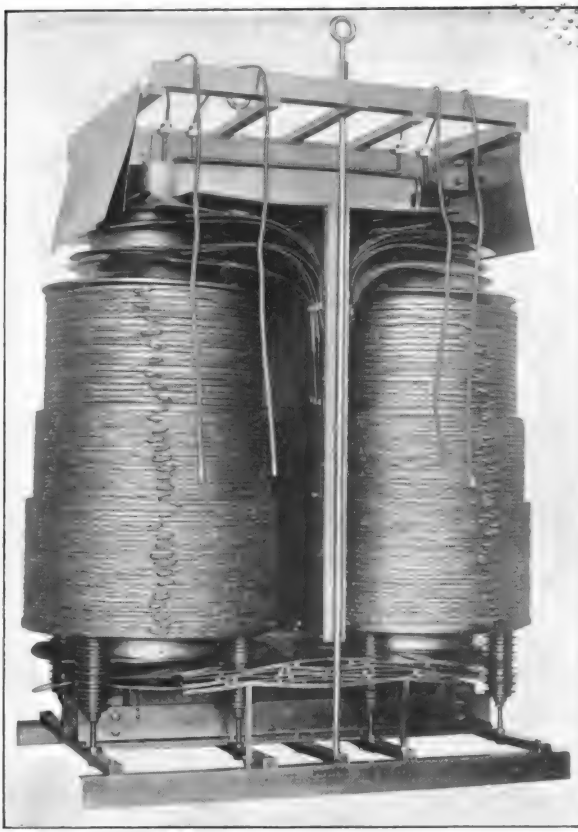


FIG. 2.—Windings of 750,000-volt Testing Transformer.

FIG. 3.—Windings of 500,000-volt Testing Transformer.

of the winding is brought out at the middle coil. The great saving in copper factor and height by adopting this method is marked.

The main considerations in connection with the winding of coils are :—

1. Sufficient and proper insulation between turns, between layers, and between sections.
2. Mechanical strength, making it impossible for any turns to become displaced.

By reference to Fig. 2, it will be noticed that the group of coils on each leg rest on a metal ring, and that the top coils are also capped by a metal ring. These rings are to prevent damage to the coils arising from discharges induced to ground, considering each leg as a condenser.

In connection with the arrangement and construction of the windings the chief points to be watched are :—

1. Proper and most economical general arrangement.
2. Sufficient insulation per turn and per coil.
3. Sufficient puncture distance and creepage surface between all points where there exists a high-potential difference.
4. Due consideration to the proper mechanical construction of both the windings, the insulation, and their support.

Insulation on End-turns.—It has been found from experience that to obtain immunity from breakdown due to the accumulation of high voltages on the end-turns of high-voltage windings, it is quite sufficient to grade the insulation at each end of the winding to a depth of only about 4 to 6 per cent., but the exact amount varies according to the standard practice of the different manufacturers. External choke coils are sometimes used in place of this special grading, as may be seen from Fig. 1.

It is not considered good practice to have either series parallel connections or tappings on the high-tension winding unless absolutely necessary, as it is desirable that the high-tension terminal gear should be as simple as possible.

High-voltage Terminals.—The main essentials which should be embodied in the design of a high-voltage terminal are, first, sufficient creeping surface to prevent a flash-over taking place between the live metal lead and the tank through which it passes, and secondly, sufficient thickness of insulation between the live lead and the tank to prevent a puncture taking place.

Glass terminals are occasionally used for 100,000 volts, but not above. Porcelain terminals have been made for use up to 500,000 volts. The "condenser" type terminal and the "oil-filled" terminal are used up to the highest voltages.

The most economical method of constructing the "condenser" type of terminal (Fig. 4 *c* and *d*) is that in which the total thickness of insulation between conductor and support is divided into a number of sections of equal thickness, separated from each other by metal cylinders

of such dimensions as to give a series of condensers of the same electrostatic capacity. The voltage across any one of these condensers will be inversely proportional to its capacity, according to the well-known law of condensers in series, with the result that the potential

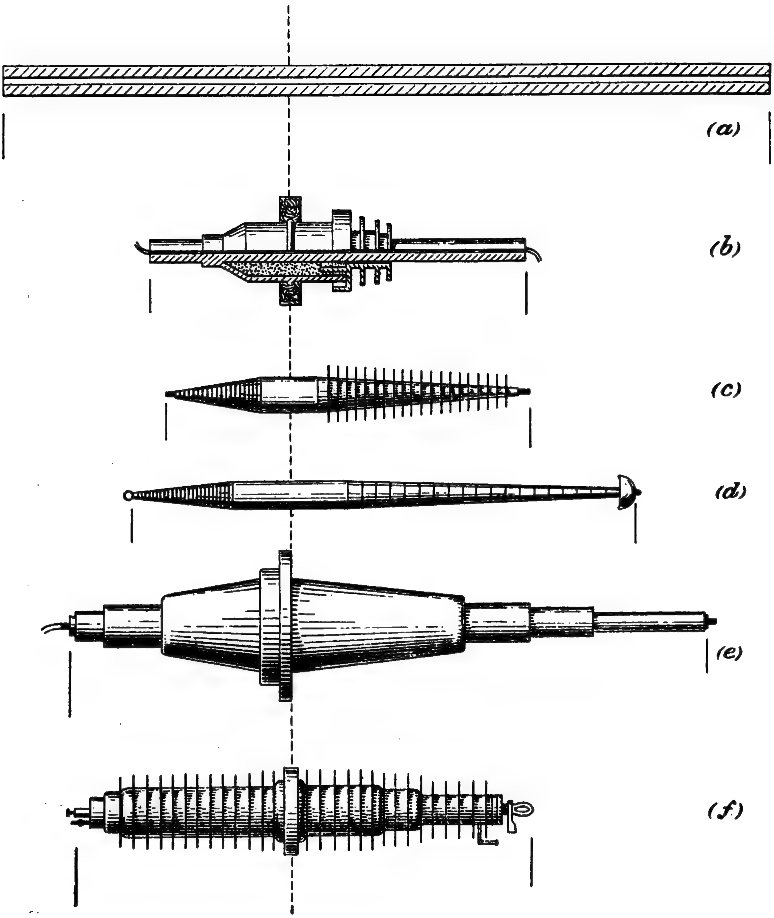


FIG. 4.—High-voltage Terminals.

gradient throughout the dielectric will be constant, and the best conditions against puncture provided for.

Since the thickness of insulation between each layer of tinfoil is the same, and the capacities are all equal, the ends of the tinfoil will lie in a logarithmic curve, so that the creepage volts per millimetre are not the same all along the surface of the terminal. If, however, the ends of the tinfoil are made to lie in a straight line, when the capacities of

the first and last condensers are equal, the exact distribution of stress may be determined from the following formula—for the capacity of two parallel cylinders :—

$$\text{The capacity} = \frac{2{,}413 \cdot k \cdot l}{10^7 \cdot \log_{10} \cdot \frac{r_2}{r_1}} \text{ in microfarads,}$$

where k = specific inductive capacity, l = length in centimetres, r_1 = inner radius in centimetres, and r_2 = outer radius in centimetres.

The result of applying this formula shows that there will be an increase in capacity of each condenser from both the inside and outside towards the centre of the terminal. This is partly compensated by leakage to ground, and by the addition of a metal cap on the top of the terminal. The result, therefore, of making the creepage potential gradient constant does not seriously interfere with the best conditions of puncture.

Another form of construction is that in which the ends of the tinfoil are made to lie in straight lines, while the thickness of insulation per layer is varied to obtain approximately equal capacities.

The "oil-filled" terminal (shown in Fig. 1) consists essentially of a built-up shell of insulating material, generally of hard wood or red fibre, in the form of short concentric cylinders, all fitting closely together and clamped tightly by the live bolt passing through the middle. This shell is then filled with a high-grade insulating liquid or compound, such as oil or asphaltum. Between the different sections are placed concentric discs of pressboard with the object of increasing the external creeping surface. In practically all cases the conductor passing through the centre of the terminal is heavily insulated from the surrounding shell by means of a number of concentric cylinders properly spaced.

Fig. 4 (*a* to *f*) shows to scale a number of different makes of terminals, all for a test voltage of 200,000 volts for 1 minute.

(*a*) Glass tube terminal.
(*b*) Porcelain "oil-filled" terminal.
(*c*) "Condenser" type terminal—The British Westinghouse Company.
(*d*) "Condenser" type terminal—The American Westinghouse Company.
(*e*) "Bulk" type terminal—The American Westinghouse Company.
(*f*) "Oil-filled" terminal—The General Electric Company, U.S.A.

In conclusion, the author wishes to express his thanks to Messrs. The A.E.G. Company, Brown, Boveri & Co., Ltd., Machinenfabrick Oerlikon, The British Westinghouse Company, Ltd., Siemens and Halske, and Siemens Bros. & Co., The American Westinghouse Company, The General Electric Company (U.S.A.), and The British Thomson-Houston Company, Ltd., for photographs illustrating their designs of high-voltage transformers.

AN ACCOUNT OF SOME EXPERIMENTS MADE WITH VARIOUS WIRELESS TELEGRAPHY TRANSMITTERS AND A COMPLETE DESCRIPTION OF AN INEXPENSIVE APPARATUS FOR USE OVER SHORT DISTANCES.

By PHILIP R. COURSEY, Student, and GRAHAME G. DAWSON.

(*Abstract of paper read before the* STUDENTS' SECTION *on 20th December*, 1911.)

This paper aims at giving a more detailed account of some apparatus employed in wireless telegraphy than was given in the general descriptions forming part of the paper previously read by Philip R. Coursey before the Students' Section (in January, 1911). It contains a brief description of some experiments that have recently been carried out on various forms of transmitters in order to test their working, reliability, etc., which are briefly referred to in this abstract.

These experiments, originally commenced on the Lepel apparatus, led eventually to the construction of the transmitting apparatus which is described below. The main objects in view in carrying out these experiments were:—

(*a*) Reliability of the apparatus,
(*b*) Efficiency of operation, and
(*c*) Cost of construction.

The first of these is probably the most important, but where small installations are concerned, the question of the capital cost of the apparatus is one that must not be neglected, particularly, for example, in the case of small ship installations, such as on cargo boats, etc.

Turning now to the experiments; we first made tests on a Lepel transmitter worked off a 240-volt direct-current circuit. (A description of this form of transmitter may be found in several articles by von Lepel and others, in the *Electrician** and other journals†; also in a paper by Dr. W. H. Eccles describing some efficiency measurements on this apparatus‡; and a description of the similar Telefunken transmitter in "The Principles of Electric Wave Telegraphy and Telephony," § by Dr. J. A. Fleming.) Experiments were conducted

* *Electrician*, vol. 63, pp. 174, 370, 374, 376, etc.
† *Electrical Engineering*, vol. 5, p. 434.
‡ *Journal of the Institution of Electrical Engineers*, vol. 44, p. 387.
§ 2nd Edition, p. 762.

both with and without water cooling for the electrodes; but the chief objection found was the comparatively short time that the paper lasted before wearing away to the edges, when the electrodes became short-circuited. The nature of the paper used between the electrodes was also found to have some influence on the stability or otherwise of the oscillations, probably due to different papers having different decomposition products when heated under the action of the discharges.

The short times found for practicable working may have been due to using the low supply voltage—about 500 volts is more suitable—and also to the fact that the electrodes used were somewhat smaller in diameter than the commercial size, but in any case the time of effective working cannot be very long.

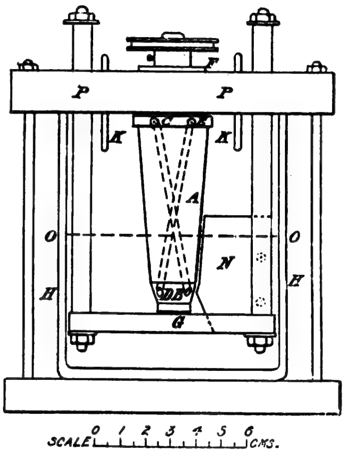


FIG. 1.—General Arrangement of Mercury Break.

Following this, a motor-driven commutator converter was used to convert the direct-current supply into alternating through the medium of a triple-coil transformer. The use of condensers of considerable capacity connected across the segments of the commutator was found to give very beneficial results, probably due to the setting up of oscillatory currents of fairly high frequency through the primaries of the transformer, and so giving an augmented secondary voltage. The alternating current from the transformer was then used to feed the Lepel gap as before, with water cooling for the electrodes, using papers up to about 0·005 cm. thickness. This arrangement resulted in a great improvement, and a considerable increase in the efficiency of operation.

The next step consisted in inserting a few drops of paraffin oil in the hole in the paper between the electrodes. The effect of this was to cause a very large increase in the energy passing out to the aerial,

and making the arrangement much more stable than the plain Lepel gap working on 240 volts direct current. The carbonisation of the paraffin oil by the discharges was its chief drawback, as it necessitated cleaning up the electrode surfaces after each run, and occasionally resulted in a short between the electrodes. The use of paraffin-waxed papers between the electrodes, without oil, gave a similar result to the actual oil in the gap, and was easier to manipulate. Running the oscillator in a bath of paraffin oil was somewhat more successful, but in any case the time of effective working was too short to be of much practical use. The commutator was, moreover, rather unsatisfactory for several reasons, and so was replaced by a motor-driven mercury break to perform the same functions. It was then found that other possibilities presented themselves, and finally the present form of apparatus was devised.

The mercury break is constructed as follows (Fig. 1). A is the pump of steel rod turned into the shape shown, and running between bearings F and G; B C and D E are holes drilled through it in a slanting direction, so that, when the pump is driven round by a small electric motor, the mercury is forced up the holes, issues as jets at C and E, and impinges on the ring of (8) contacts K K. These contacts are connected together alternately, and leads brought out to two terminals, a third terminal being connected to the mercury contained in the cylindrical glass jar H H, as at O O. P is the insulating cover to the glass jar, bolted down to the base as indicated. N is a vane of sheet iron to prevent the whole mass of mercury from being carried round by the rotation of the pump. Either one or two jets may be used, as desired, by plugging one or other of the holes in the pump A. Hence, when the pump revolves, the mercury is connected alternately to the other two terminals of the instrument.

Various arrangements of circuits have been tried in connection with this apparatus, but they can be divided into two main groups, which may be named respectively as—

1. The "discharge" method.
2. The "charge-and-discharge" method.

The connections for these are given in Fig. 2. In this figure B represents the mercury break, with terminals T_1 and T_2 connected to the alternate sets of contacts, and T_3 to the mercury. L_1 and L_2 are choking coils in the supply leads (best effects were found when the combined inductance of the coils, which were wound together, was 0·14 henry, with the apparatus employed). R is the steadying resistance in the leads, and K the signalling switch or key. C_1 is the primary, or break, condenser of capacity about 2·7 microfarads, in our experiments, and L_3 is the inductance forming the primary of the jigger J, through which the condenser discharges. The secondary L_4 of this jigger feeds an ordinary spark transmitter, forming circuits III. and IV., as sketched, L_7 being the tuning inductance in the aerial circuit. To obtain full advantage of the arrangement, circuits I. and II.

should be resonated; that is, $C_2 L_4$ should be made $= C_1 L_3$ while, of course, circuits III. and IV. should also be in tune. Circuits III. and IV. will not have the same frequency as that of I. and II., being about 10^6 cycles per second (*i.e.*, for a wave-length of 300 metres), while circuits I. and II. may conveniently be given a frequency ($n = \frac{5{\cdot}033 \times 10^6}{C_1 L_3}$; C_1 in microfarads, and L_3 in centimetres) of about 50,000 cycles.

Experiments conducted on the break, using varying numbers of contacts from 1 to 16 and running the break at various speeds, showed

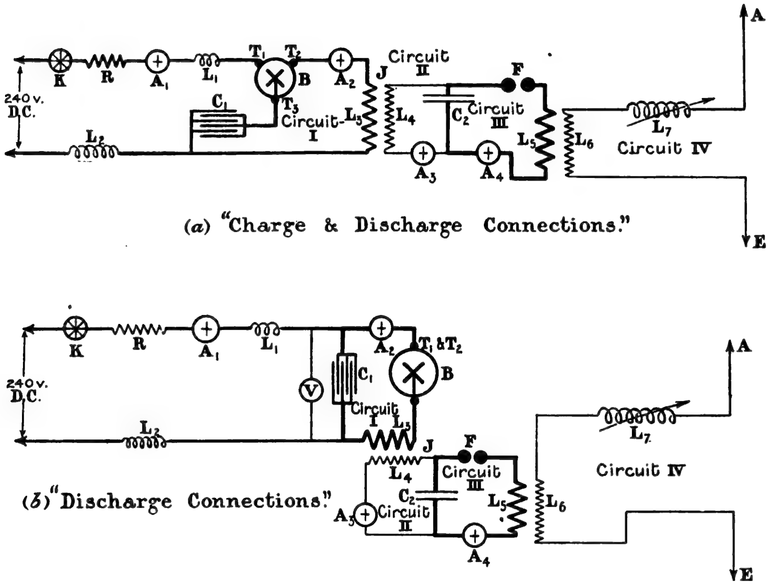


FIG. 2.—Connections of Mercury Break.

that best effects were obtained using 8 contacts, with speeds between 3,000 and 4,000 revs. per minute, although the actual value of the speed for best results, showed by a marked diminution of the sparking in the break, had to be determined by trial for each arrangement of the apparatus.

The results obtained with the "charge-and-discharge" connection were not quite so good as those with the "discharge" method, for two reasons, viz.:—

1. Insufficient capacity of the condenser C_1.
2. Leakage of the charge of the condenser between the period of charge and the instant of discharge by the next contact.

The arrangement of the connections according to the "charge and discharge" system has, however, its uses; and it is moreover much less wasteful of power than the "discharge" connection, as, since in the "charge" position the circuit is only closed through the condenser, the series resistance need not be used, thus eliminating the C^2R loss therein and making it in fact the ideal connection as far as efficiency is concerned; although probably if the condenser had been better insulated than it was during these tests the discharge currents would have been considerably larger.

In our experiments the jigger J was first an open-circuit iron core transformer, but at these high frequencies the iron loss was very excessive, so that it was found possible by suitably designing the jigger for resonance, as above, to dispense with the iron core and use an ordinary

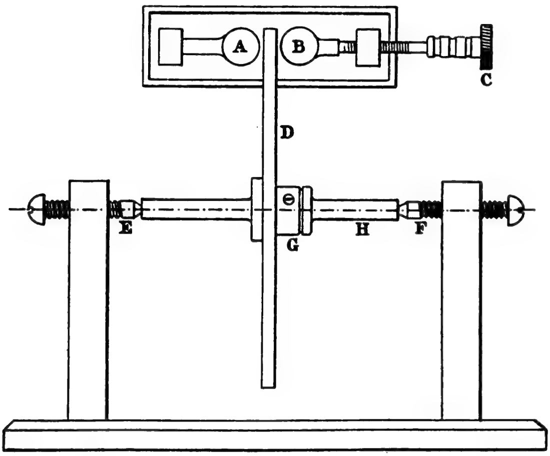


FIG. 3.—The Rotary Disc Discharger.

air-core jigger, the dimensions of which are much smaller than those for an iron-cored transformer for the same output, as the losses are much smaller; and further, the effects of resonance between circuits I. and II. (in Fig. 2) can be much better utilised, especially as, by eliminating the iron core, the frequency of these circuits can be raised.

In connection with the transmitter proper an improvement was obtained by using a spark-gap having a brass disc rotating between the knobs, as shown in Fig. 3, instead of the plain knob-gap. The disc may be rotated by a small motor, and helps to extinguish any arcs that may form in the gap by causing an air draught between the knobs and providing a cold metal surface for the sparks. In Fig. 3, D is the disc running between adjustable centres E and F and rotating between the spark knobs A and B.

A modified form was subsequently designed—Fig. 4—in which both electrodes are water-cooled and one rotates relative to the other. A

and B are the hollow cylindrical electrodes, A being fixed to the insulating frame C D E. B runs on the fixed shaft F G, which passes through a hole in A (with sufficient clearance to prevent sparking). A spring M on the shaft also passes through the hole in A, and bears against a boss projecting from the face N of the electrode B. V is the spark-gap between zinc faces, and P a screw to adjust the length of the gap. Water passes into the fixed electrode by tubes R and S, and to the moving electrode through the hollow shaft at Q and T.

Hence the chief features of this form of transmitting apparatus are, first, the use of a motor-driven mercury break to convert, through the medium of a condenser, directly from a direct-current supply (at about 200 to 250 volts) to high-frequency alternating current which can then be transformed up for use in an ordinary type spark transmitter by means of an air-core jigger of comparatively small dimensions; secondly, the low cost of construction as compared with that of ordinary wireless apparatus used in commercial stations; and thirdly, the fact that it can be worked off an ordinary direct-current power or lighting circuit.

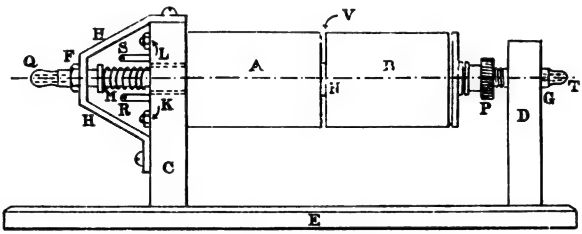


FIG. 4.—Water-cooled Spark-gap.

Of course, in designing a large station for commercial transmission of public messages, it is general to put in suitable machinery that will give the alternating current required for use with the step-up transformers to raise the voltage enough to operate the spark-gaps of the transmitter; but when smaller stations have to be considered for private use and for short distances of transmission the ability to use the ordinary supply circuits is an important matter. When an alternating-current supply is available a transformer can be used directly, but would probably cost as much, if not more than, this apparatus as a whole; while if only a direct-current supply is available, as is more usual, it would be necessary to put in a rotary to convert to alternating current, and then to use a step-up transformer to feed the spark-gap of the transmitter itself, or else to employ an induction coil worked from an accumulator battery which could be kept charged from the direct-current mains, but would in either case be more costly than the alternating-current arrangement.

Finally, we have to express our thanks to Professors Fleming and Clinton, of University College, London, for permission to carry out some of the measurements in the Laboratories of the College.

THE TRANSMISSION OF ELECTRICAL ENERGY BY DIRECT-CURRENT ON THE SERIES SYSTEM.

By J. S. Highfield, Member.

(*Paper received 8th February, received in final form 13th April, and read at the* Glasgow Meeting of the Institution *on 12th June,* 1912.)

Introduction.

In my paper of 7th March, 1907, bearing the above title, I had the privilege of putting before this Institution some facts and theories in regard to this very interesting system. There I endeavoured to show that it possessed certain advantages over the alternate-current parallel system which rendered its adoption under some circumstances advisable, and that for certain specified applications the constant current series motor possesses peculiar advantages. I also dealt with general considerations governing the design of this system under varying conditions.

Since writing that paper matters have progressed. After the most careful consideration, the Metropolitan Electric Supply Company decided to use the series system for supplying their western area, and the plant was put to work in March of last year and has been running steadily ever since; two sets of winding gear have been constructed, and the Moutier-Lyon system (the largest series transmission yet erected by M. Thury) has been largely extended.

The western area system of the Metropolitan Company is designed ultimately to feed an area containing 300 square miles, the extreme distance by road to the remote points from the power station at Willesden being about 28 miles. The Company hold, and are now working, the Orders in Southall, Hanwell, Brentford, and Acton, and possess bulk supply powers in the remaining districts to which it is not certain when the opportunity will arise for giving supplies.

Owing to the small load existing in a great part of the district, the important matter was to design a system which would involve the least possible cost in mains and at the same time admit of ready and inexpensive expansion to meet the requirements of a rapidly increasing population. It was also necessary to use a system which, while being inexpensive for short distances, could be readily extended to very long distances. Another consideration to be kept in view was that at some future date it might be advisable to carry the supply to still greater distances. In short, it was realised that a system having these particular

advantages might be of great commercial value, and in view of the fact that the immediate cost for the present short distance was not greater than that of other systems, it was decided that the possible future commercial value was sufficiently great to warrant a departure from existing methods.

Portions of the area are already supplied by existing companies and local authorities, some by alternating and some by direct-current systems, and it is contemplated that in time some, or all, of these may think it wise to supplement their present plants with a bulk supply. In such cases it is usually found that it is for a time economical to use the bulk supply for part of the load and to employ the existing plant to supply the peak load. In order to utilise the bulk supply to the best advantage, it is necessary to work it in parallel with the existing plant. In the case of an alternating-current plant it is very difficult to take a supply at a different frequency and to work the necessary

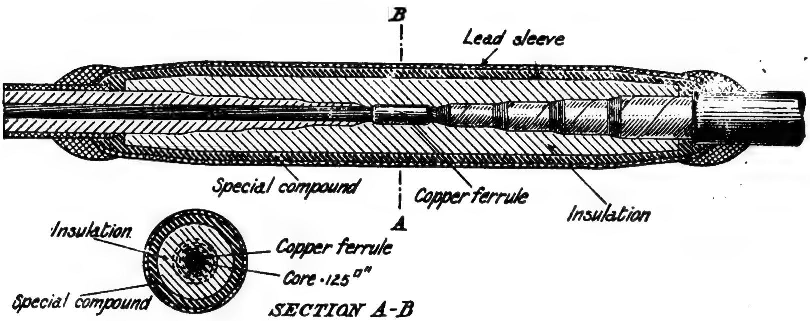


FIG. 1.—Joint for 100,000-volt Lead-covered Cable.

phase-changing motor-generator in parallel with the local plant. With the series system parallel running in such cases presents no difficulty.

It was decided to lay mains having a capacity of 10,000 k.w. with sufficient reserve in the case of breakdown, and after much research it was found that two single-conductor cables having a core of 0·125 sq. in. section with ½ in. of paper insulation sufficient for 100,000 volts direct current could be laid in iron pipe at less cost than any other system of similar capacity. To provide for continuity of supply in case of breakdown of one of the mains, it was desirable to use the earth as the spare conductor. Further research having shown that this was possible without risk of interference with other electrical circuits, this method, with the consent of the Board of Trade, was decided upon ; thus, the cost of a third or standby cable was avoided.

For the secondary supply the mains are of much less capacity, and can be tapped at frequent intervals to supply small sub-stations for town and village lighting and fairly large power consumers. A somewhat high pressure being necessary for this purpose, it was decided to

use 3-phase alternate-current mains at 3,000 volts pressure, and for the low-tension system supplying small consumers a 3-phase 4-wire system at 415 volts pressure between phases. This network showed lower costs and greater convenience than any other. The comparatively high secondary pressure enables an area of about 10 square miles to be worked from each sub-station. Thus in spite of the scattered nature of the demand each sub-station will grow to considerable dimensions, enabling larger plant to be used.

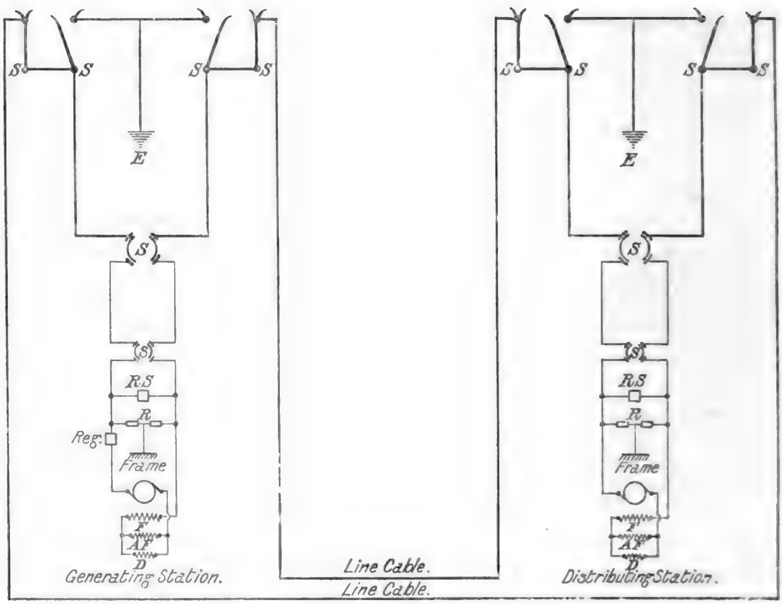


FIG. 2.—Diagram of Connections.

S Main line switch.
RS Short-circuiting switch.
F Main field.
S_1 Earth switch.
S_3 Operating switch.
AF Auxiliary field.
S_2 Isolating Switch.
R Balancing resistance.
D Diverter.

Cable System.—The transmission cable system, as already stated, consists of two plain lead-covered paper-insulated cables drawn into cast-iron pipes of 2½-in. inside diameter, the pipe joints being made with yarn and clay and being electrically bonded by means of three corrugated iron wedges which bite into the iron. These wedges make a very good joint and are inexpensive. Special split cast-iron boxes are used to hold each cable joint, and small split boxes are used at bends. There are no brick pits or surface covers; the cable is surrounded throughout its length by cast iron, thus the cable is admirably

protected. The present system supplies from the power station to Southall, a distance of about 7 miles.

The joints in the cables are made with paper on a method developed and used by the Metropolitan Company for some years on the 10,000-volt concentric cables, and described by me in the discussion on a paper by C. Vernier on "The Laying and Maintenance of Transmission Cables."*

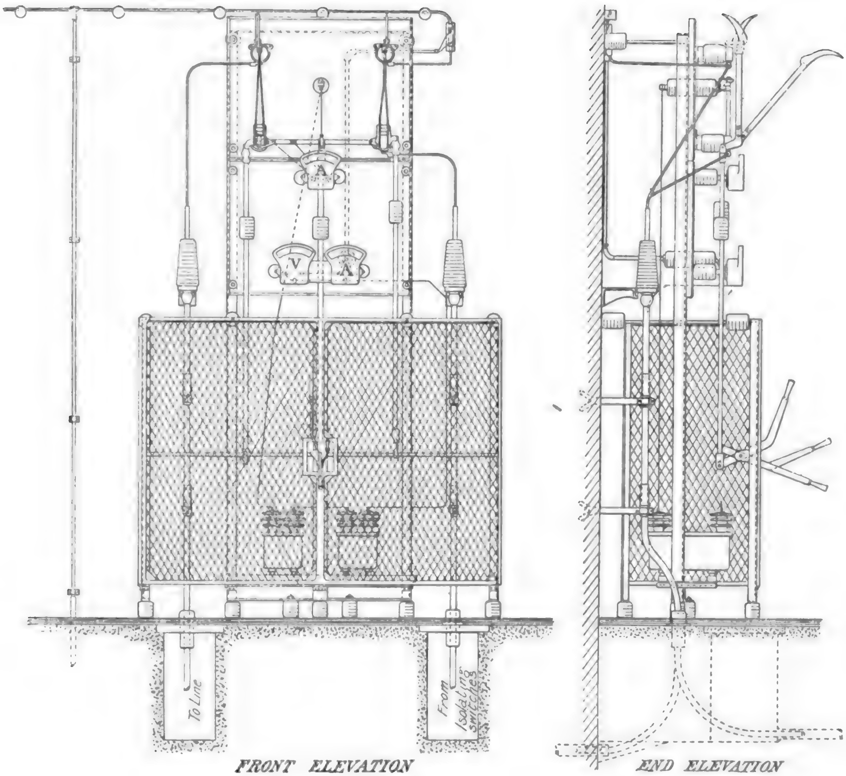


FIG. 3.—Main Switchboard with Line and Earth Switches and Instruments.

These joints are shown in section in Fig. 1. They are made in the following way: The lead is first carefully removed. Steps are made in the paper insulation by carefully unrolling each layer and tearing, not cutting, it off so as to form four steps. The conductors are joined by a sweated sleeve and the whole is covered by a paper ribbon 1 in. wide wound on to the joint off a reel. In this way the paper is never handled, and consequently moisture is not left in the joint. A lead

* *Journal of the Institution of Electrical Engineers*, vol. 47, p. 339, 1911.

sleeve is then drawn over the joint and plumbed to the lead sheath of the cable. It is then filled with compound. They are inexpensive and have proved themselves most reliable.

Each cable length of 220 yards was tested in the factory to 75,000 volts alternating current at 60 cycles, the pressure being applied for 10 minutes; a 6-ft. piece of each length manufactured was tested to 130,000 volts alternating current at 60 cycles, which pressure was resisted for about 5 minutes; the type of joint used was tested up to 150,000 volts 60 cycles without breaking down. After laying, the whole length of cable was tested to an alternate-current pressure of 20,000 volts 60 cycles every 35 minutes.

Cable testing by alternate current is not satisfactory unless a low

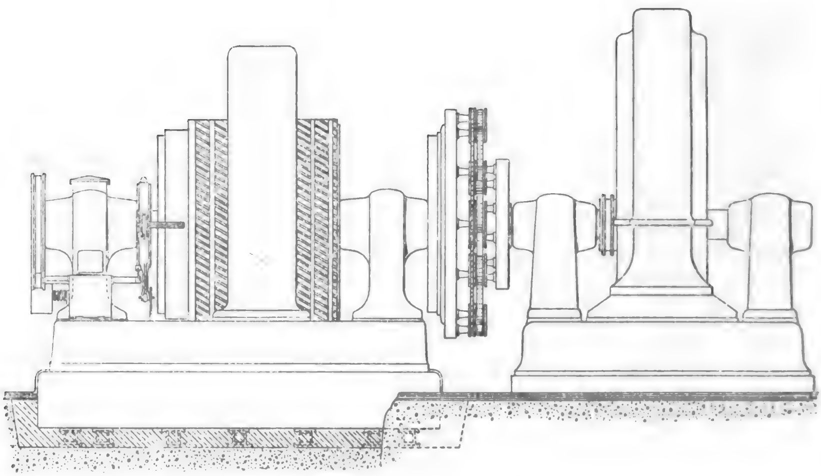


FIG. 4.—Motor-generator showing Insulated Foundations.

Generator output: 100 amperes 5,000 volts.

frequency is employed, and a low frequency necessitates the use of very large transformers in order to supply the charging current; this is particularly difficult where very high pressures are required. Consequently, it was decided to test the cables with direct current at a pressure of not less than 150,000 volts. In order to obtain this pressure a special machine was constructed of a similar type to that used by Mr. Watson in the experiments he has described to this Institution, but having a greater capacity. The machine consists of a generator of the Voss type, direct driven by a motor at about 1,000 revs. per minute. The generator and motor are completely enclosed in a cast-iron case, the high-tension terminals for the supply to the motor being brought through the case by large ebonite insulators. The case is then filled with nitrogen at a pressure of 200 lbs. per square inch. The motor is supplied with current from

the small generator which, of course, owing to its direct connection with the motor, is charged at the full pressure ; it is therefore necessary to insulate this generator from earth in the same way as the whole machine is insulated. This generator is in its turn driven by a motor by means of two wooden pulleys and a cotton rope which provides ample insulation for the maximum pressure given by the machine. Small mechanical defects occurred in the machine and caused delay in carrying out the tests which, in fact, have not yet been completed. When connected to one cable with its switchgear the machine maintained, for periods of about 30 minutes, a pressure of 130,000 volts, and for short periods a pressure of 150,000 volts, the total energy put into the cable and switchgear being approximately 500 watts, this

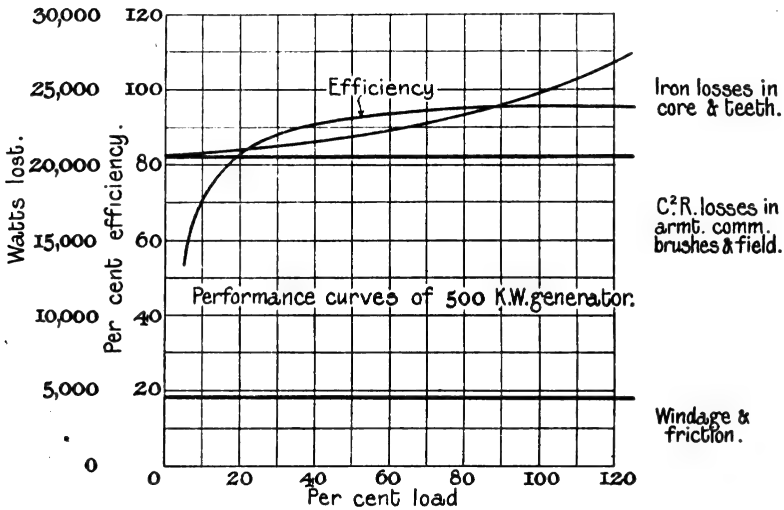


FIG. 5.—Performance Curves of 500-k.w. Generator.

leakage being due to small discharges at various points. The pressures were measured by a single-cell Kelvin type voltmeter working in compressed air at a pressure of 200 lbs. per square inch.

I regard the construction of this machine as a notable achievement, and think that Mr. Watson and the makers are greatly to be congratulated.

It is proposed to continue these tests with an improved apparatus, as much information is required, not only in regard to the insulation of the cables, but also in connection with the machines and foundations. The tests already carried out, together with the experience of the Moutier-Lyon plant, are, I think, quite sufficient to prove that the cable system can be successfully worked at a pressure of 100,000 volts.

The whole of the connections and switchgear for the cable system

and for one generator and one sub-generator are shown diagrammatically in Fig. 2.

Switchgear.—Each end of each cable is connected to its own switching panel shown in Fig. 3. The panel contains two switches, one for coupling the cable to the power station or sub-station circuit, and the other for coupling the station circuit to earth. The two switches are interlocked, so that it is impossible to draw one until the other has been closed. The instruments consist of an ammeter in the line, an ammeter in the earth circuit, and a voltmeter to show the pressure between the line and earth; the latter is provided with a switch, so that it can be conveniently disconnected from the circuit. The panels provide for double insulation, the various instruments and switches being carefully insulated with large porcelain insulators from the panels; the frames carrying the panels are again insulated from earth. It is a special advantage of the series system that, with the exception of the cable, it is possible to provide double insulation at all points.

Power Station Plant.—It was decided to drive the first machines by means of synchronous motors supplied with energy from the alternate-current generators already installed in the power station. Later on, when steam-driven direct-current sets are installed, these machines will form a convenient link between the direct and alternate-current systems. There is nothing special about the synchronous motors, which were machines already in the possession of the company. It was for this reason that so low a speed as 200 revs. per minute was chosen for the direct-current generators.

The direct-current generators shown in Fig. 4 have 6 poles. The commutators are 60 in. in diameter and 6¾ in. long, and contain 1,439 segments. Since the maximum current to be collected is 120 amperes, only two sets of brushes are required. Consequently, not only does the commutator run almost without noise, but the wear is inappreciable. The machines are designed to run sparklessly at any load, but will allow the current to be varied from 70 to 120 amperes. The normal pressure is 5,000 volts; this is the highest pressure for which a machine of this type has, so far, been designed. Therefore the output of the machine at 100 amperes is 500 k.w. and at 120 amperes 600 k.w. The performance curves of these machines are shown in Fig. 5 and the armature in Fig. 6.

The current is maintained constant by a regulator which serves to regulate the working field by moving the brushes from full to no-load position, and at the same time shunting a part of the field current by means of a diverter. The regulator, shown in the photograph Fig. 7 and in the diagram Fig. 8, is driven by a small belt from the end of the generator shaft. It consists of a small turbine wholly submerged in oil. The turbine serves to maintain a pressure of about 25 lbs. per square inch. In the case containing the turbine is a vertical cylinder in which moves a gate on a vertical shaft through a segment of the cylinder. This gate is immersed in oil, and the supply under pressure from the turbine can be directed to either side, so as to rotate with great

FIG. 6.

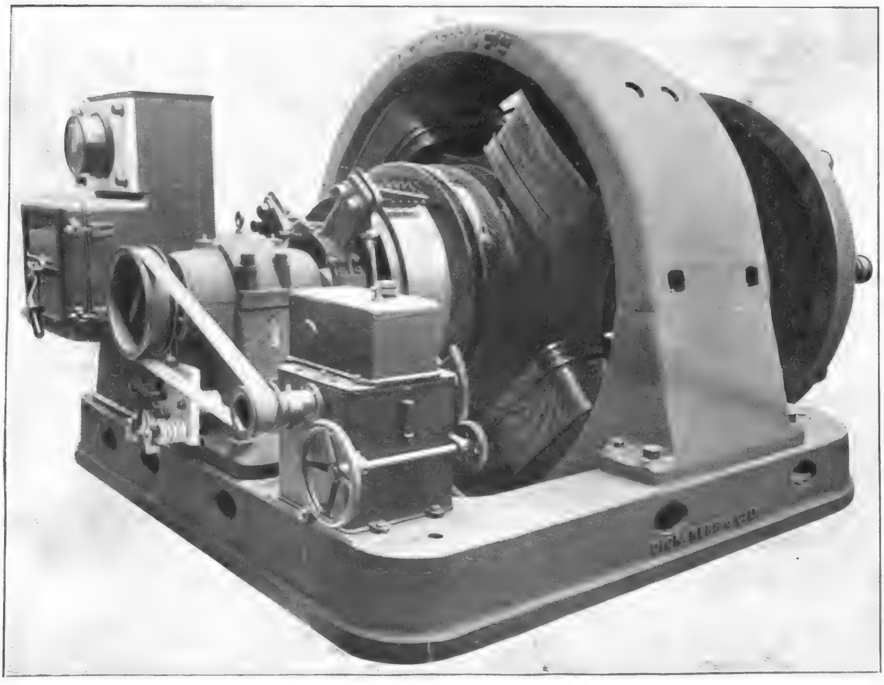


FIG. 7.

force the shaft to which it is attached. This shaft is geared by means of bevel wheels to a horizontal shaft, which acts directly on the brush rocker. The supply of oil from the turbine is taken through a small piston valve, which serves to distribute it to either side of the gate above mentioned. The position of the main valve is controlled by a solenoid through which the main current passes, pulling against a spring and controlling a relief valve. It will be seen that the governor is of the relay type, and that any variation in the current through the solenoid changing the direction of the flow of oil brings a very large force into action to move the brush rocker and diverter

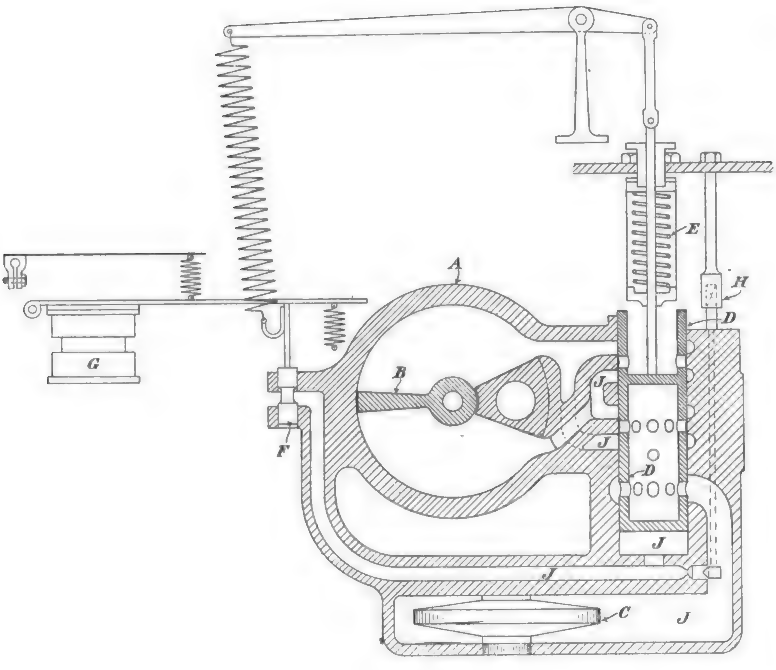


FIG. 8.

switch. The rocker is mounted on roller bearings, so that it will move with great ease, and, owing to this, and the great force exerted by the regulator, there is very little possibility of failure. In addition to the main spring, there are additional springs to prevent hunting and to provide for the even distribution of load between the machines. The changes in load on the system are not very rapid, and consequently the regulators are not adjusted for regulating at very great speed, but the type of regulator is capable of being adjusted for handling variations from no load to full load taking place in less than 1 second.

The generators are driven through an insulating coupling of the

Zodal type consisting (as shown in Fig. 4) of two discs fitted with pins and rollers for carrying the main forward driving belt and reverse belt which is necessary to enable the set to be started from the direct-current end and to keep the whole coupling rigid. This coupling has also a slipping member which is essentially a disc form of clutch. This

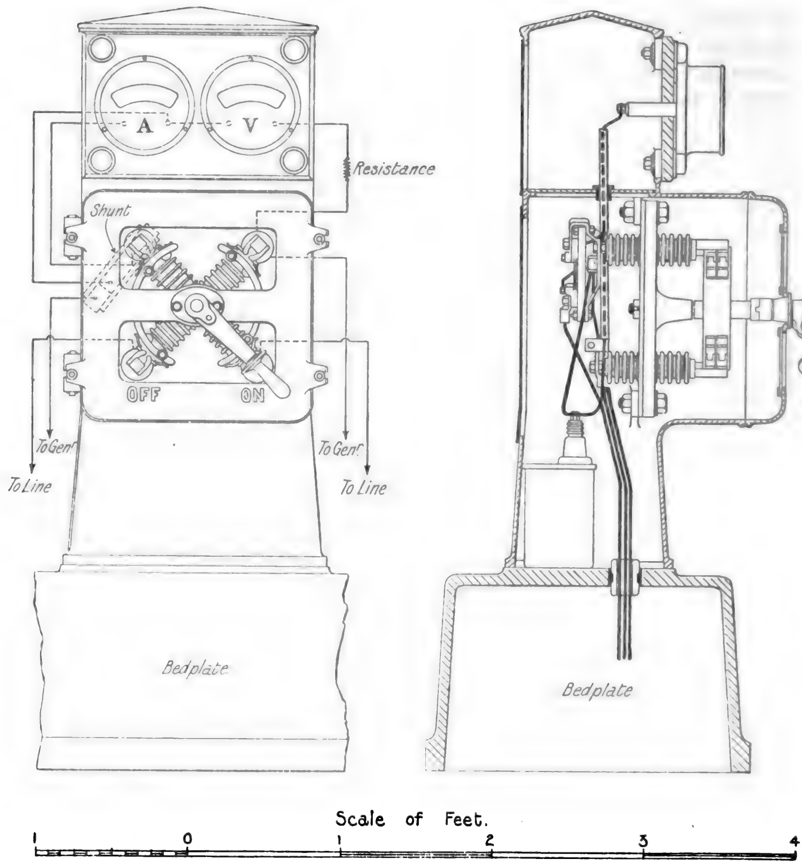


FIG. 9.—Generator Switch and Instrument Pillar.

is set to slip when the load on the generator exceeds 25 per cent. overload. If the action of the governor could be made instantaneous this slipping coupling would not be required; but it is a useful device to prevent damage to the generator, and, by slipping, it gives time for the regulator to bring the brushes to the right position to meet sudden changed conditions of load on the system.

The regulators used on these machines are naturally a great

improvement on those employed on some of M. Thury's earlier systems, and, although this plant has been running only some nine months, further improvements have been made in the regulators and safety devices, and it is probable that, in consequence of improvements in the generator and regulator design, it will be possible to dispense with the slipping coupling in future sets.

In addition to the regulator each generator is fitted with a short-circuiting switch and operating mechanism, which short-circuits the machine in the event of reversal of direction. This could happen under certain conditions; for instance, if the coupling belt broke on one generator out of several in series, this machine would pull up and reverse its direction; as soon as this occurred the switch would short-circuit the machine and cut it out of circuit. The operating switch shown in Fig. 9 for putting the generator into circuit consists of a four-point rotary switch. This is mounted on a pillar, which also carries a carbon break switch, which works in parallel with the rotating switch in such a way as to prevent damage to the latter by the arc formed when the inductive circuit of the generator is opened. In addition the pillar carries an ammeter to show the current given by the machine, and a voltmeter for measuring the volts across the terminals. It was decided to mount the switch pillar on the frame of the machine. This method is a great improvement on the old one of using a separate pillar; it makes a neater job, is less expensive, and is more secure.

In addition to these switches on the machine isolating switches are fitted under the floor for the purpose of disconnecting the machine switches from the circuit. These switches are shown in Fig. 10; they are four-point switches similar to those fitted on the machines but having considerably larger spaces. The switch works under oil, and the cast-iron box containing the switch is itself enclosed in a cast-iron box, from which it is insulated by large porcelain insulators. These switches have all been tested with a pressure of 110,000 volts alternate current applied for about 10 minutes.

The generators themselves are carefully insulated from earth. The details of the foundations are shown in Fig. 4. The generators are bolted to concrete blocks, which are supported on stoneware insulators embedded in highly insulating asphalte, the space round the beds being filled in with pure bitumen. This makes a very much sounder job both mechanically and electrically than the older method of supporting the machines on pot insulators.

The object of the whole design of the cable and gear inside the station is to make it practically immune from either mechanical or electrical breakdown; all live metal is doubly insulated from the point where the cables are attached to the switchboards.

The floor itself is constructed of concrete, on which asphalte to the thickness of 2 in. is carefully laid. It was necessary to exercise the greatest care in laying the asphalte in order to provide the highest possible insulation. Careful tests were made on the asphalte to ascertain its insulating properties, and experiment dicated that a floor

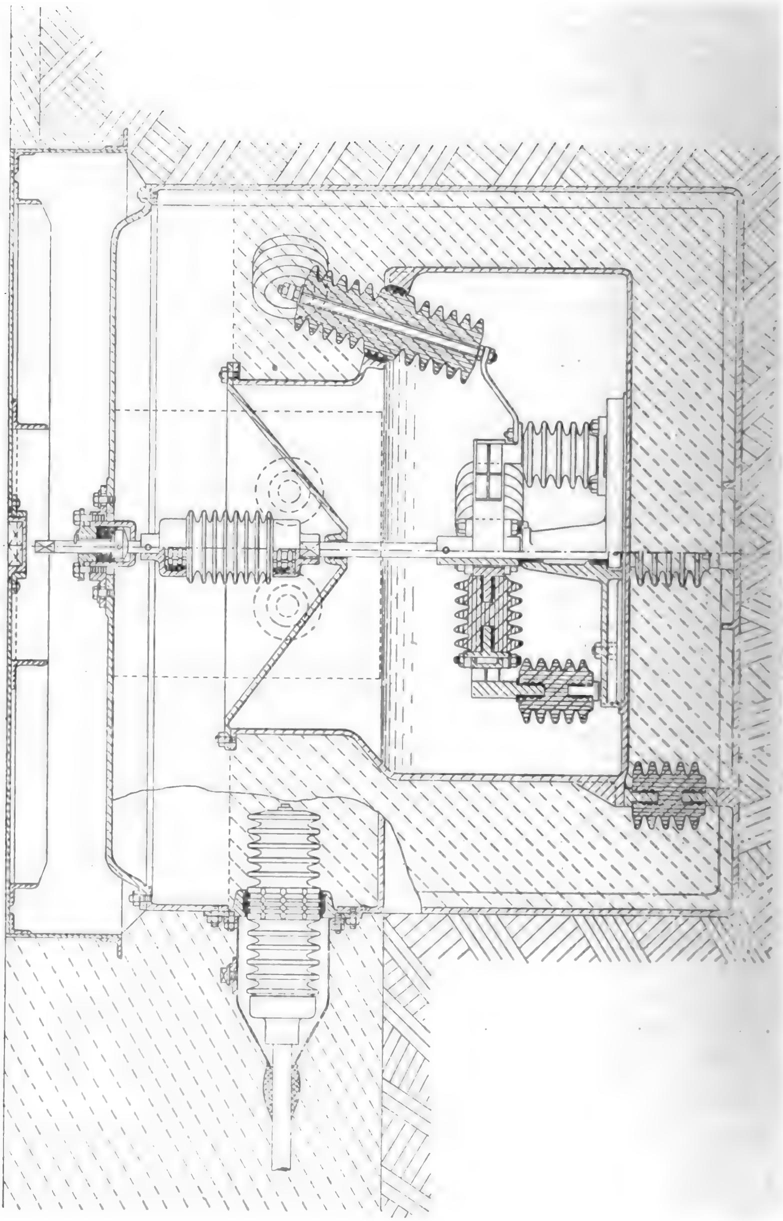


FIG. 10.—Main Isolating Switch.

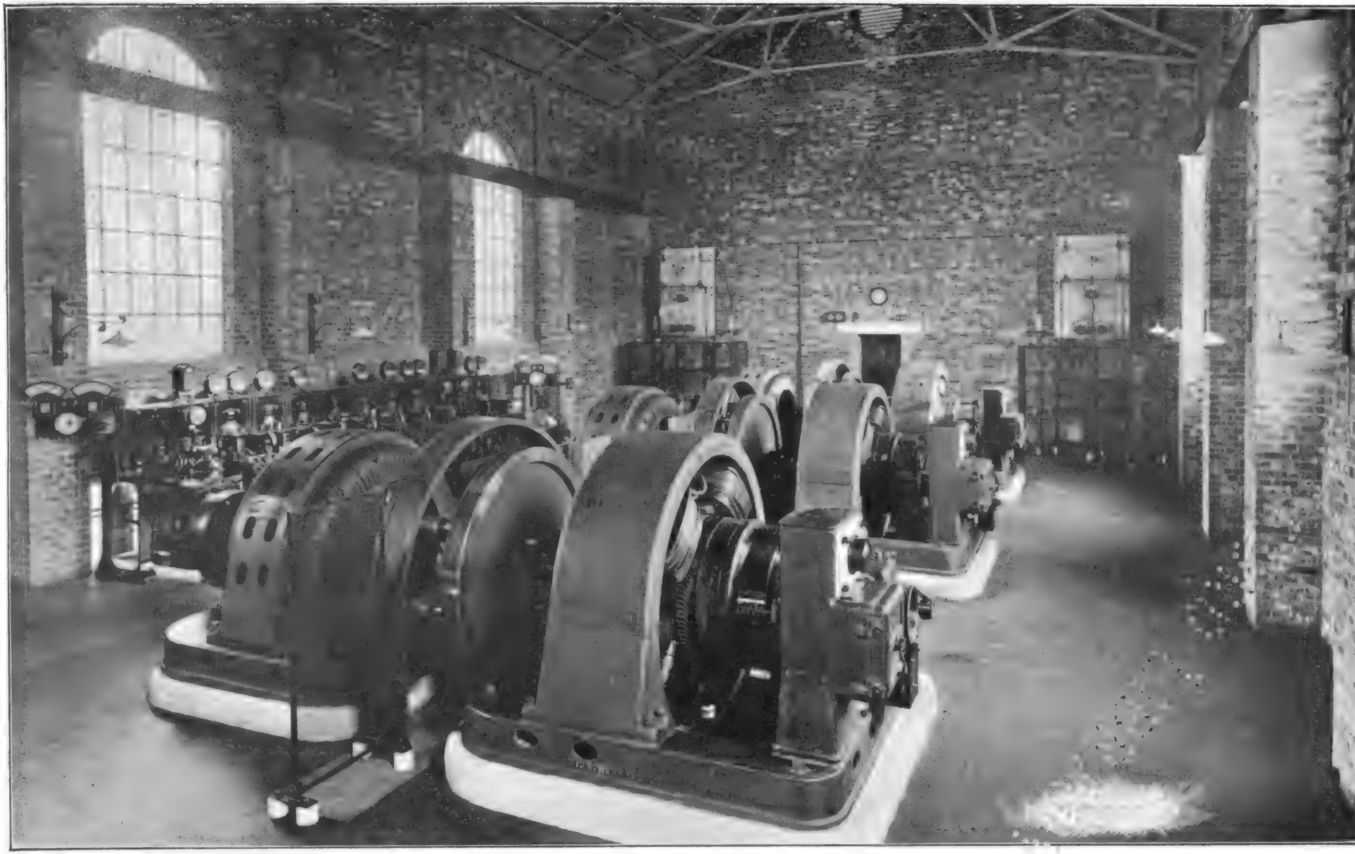


FIG. 11.

constructed in this way would require many hundreds of thousands of volts to produce a puncture.

In machines designed for such high pressures it is important to limit the pressure that can occur between either pole of the machine and the frame, thus not only reducing the stress on the insulation, but at the same time limiting any possible danger from accidental contact with live parts of the machine. For this purpose a resistance of 0·8 megohm is fitted to the machine frame, the ends being connected across the terminals of the machine. The centre point of this resistance is connected to the frame of the machine, and, consequently, the total pressure between either pole and the frame is limited to half the pressure given by the machine, and an operator standing on the frame of the machine and touching one pole cannot receive more current than the high resistance will allow to pass. Guards are provided on each machine to prevent accidental contact between the insulated

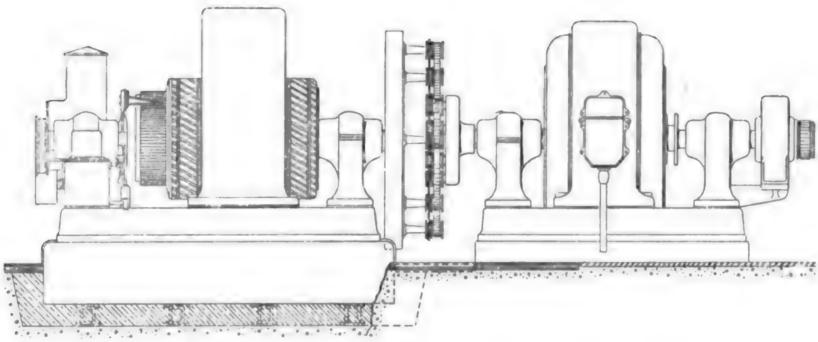


FIG. 12.—Motor-generator showing Insulated Foundations.
Generator output: 250 k.w., 3,000 volts, 50 ~, 3 phase.

frame of the direct-current machines and the earthed frames of the alternate-current motors.

Three motor-generators are now installed at the power station, two being fitted with alternate-current motors for starting from the alternate side, the third machine being always started by means of the direct-current generator.

Sub-station Plant.—The plant at Southall, shown in the photograph (Fig. 11), consists of three direct-current motors (shown in Fig. 12) driving three 250-k.w. generators supplying 3-phase energy at 3,000 volts 50 cycles. The machines run at a speed of 500 revs. per minute.

Owing to the high speed at which these machines run, they are, for their output, smaller, and the commutators are smaller than the generators at the power station. The motors drive the generators through an insulating coupling of a similar type to that used at the power station, but they are not provided with a slipping member. The speed of the machines is kept constant by a regulator of a similar type to that

employed at the power station, with the exception that in place of the piston valve being controlled by a solenoid it is controlled by the pressure supplied by the oil turbine. This pressure is balanced against a spring. Since the pressure given by the turbine varies with the square of the speed, a very sensitive speed governor is obtained. Any increase in the speed of the turbine produces an increased pressure which acts on the piston valve which serves to convey the pressure to one or the other side of the gate which controls the position of the brushes. The motor regulator is provided with a supplementary spring, which prevent shunting in the same way as the springs on the generator regulators.

The switchgear in the sub-station is precisely similar to that in the power station, panels of the same type being fitted; the mains are carried to isolating switches from which cables are laid to the starting switches on the machines, the only difference being that ammeters are not required on the motors, and consequently are not fitted.

The generators are connected to the main switchboard, from which the 3,000-volt feeders are carried to the sub-station.

The earthing switches are connected to the earth-plates in a similar way to those at Willesden.

Earthing Methods.—Before describing the actual method of operating the system, it is desirable to give a short description of the considerations which led to the final adoption of an earth return. The commercial advantages were, of course, at once apparent, but before deciding upon the use of the earth for regularly carrying considerable currents, it was necessary to make sure that such use would not cause interference with other electrical systems, and would not cause damage to property.

M. Thury has carried out a great deal of work on this subject, and both the French and Swiss Governments have appointed committees to inquire into the matter. The town of Lausanne was supplied from Saint Maurice through a single conductor with the earth as the return for 443 days continuously. Iron earth-plates were used, and during the whole time of their use it was found that their resistance changed very little. The current was 150 amperes, and theoretically the plates should have been oxydised away in less than two months, but apparently after a layer of oxide has been formed further action is very slow. The total resistance of the earth connections was about 1·6 ohms, and it was found that no inconvenience was experienced in connection with telegraphs and telephones.

The Swiss Commission is still at work on this subject, and doubtless their report, when issued, will contain much valuable information on this interesting subject.

The geological formation of the Rhone Valley is, of course, altogether different from that near London. It is, in fact, not nearly so favourable for the purpose, consisting largely of highly insulating rock, and the layer of soil and other conducting material is comparatively thin. Further than that, the Rhone water is so pure that its

conductivity is exceedingly bad; it would be truer to state that its insulating properties are high. Consequently, it was felt that before arriving at any decision as to the possibility of the successful use of the earth near London, further experiments were necessary, and it was decided that, in any event, the earth-plates should be situated at a considerable depth below the ground surface, and that connection should be made to them by insulated cables in order to avoid stray currents in the neighbourhood of the plates.

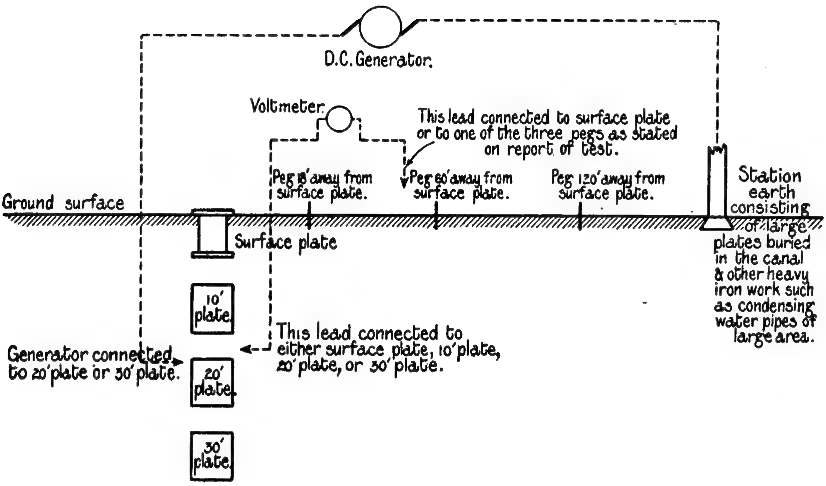


FIG. 13.—Showing Earth-plates and Connections.

The experiments were carried out in order to obtain the following information, namely:—

(*a*) At what depth below the surface must the plates be buried in order that the effect of currents at or near the surface should be negligible.
(*b*) The size of plates to be used and their number.
(*c*) The distance apart at which the plates should be situated.
(*d*) The value of the earth resistance and its constancy.

In short, the experiments were undertaken to ascertain the best method of adapting the earth as a permanent conductor for industrial currents in such a way as to avoid interference with telegraphs, telephones, or other users.

With the first object in view four iron plates were buried in the earth, situated vertically above each other, as indicated in the diagram (Fig. 13). The area of each plate was 4 ft. × 2 ft. 2 in., with the excep-

tion of the top plate, which consisted of a length of 6 in. pipe. These plates were made one pole of a circuit, the other pole consisting of large masses of iron buried in the ground round the works, chiefly condensing water pipes of very large size which make an excellent earth, the resistance of which was found to be negligible as compared with the resistance of the test-plates. A steady current was then passed between one of the plates and the station earth, measurements being made between the various points by means of a Kelvin electrostatic voltmeter for the high readings and by a moving coil voltmeter for the low readings.

The following observations were made, namely :—

1. With a steady current of 20 amperes passing between the earth-plate, 20 ft. deep, and the large main earth, the measurements were :—

Between the Earth-plate and—

A point 120 ft. away	165·0 volts.
A point 60 ft. away	165·0 „
The surface earth-plate...	163·5 „

Between the Surface Earth-plate and—

A point 120 ft. away	0·024 volt.
A point 60 ft. away	0·016 „

Between the Earth-plate, 10 ft. Underground, and—

A point 120 ft. away	0·035 „
A point 60 ft. away	0·024 „

2. With a steady current of 21 amperes passing between the earth-plate, 30 ft. deep, and the large main earth the measurements were :—

Between the Earth-plate and—

A point 120 ft. away	135·0 volts.
A point 60 ft. away	134·5 „
The surface earth-plate	133·5 „

Between the Earth-plate, 10 ft. Underground, and—

A point 18 ft. away	0·008 volt.

Between the Surface Earth-plate and—

A point 120 ft. away	0·020 „
A point 60 ft. away	0·010 „
A point 18 ft. away	0·004 „

3. With a steady current of 21 amperes passing between the surface earth-plate and the main earth, pressure readings were taken between the surface-plate and spikes driven into the ground at various points. The results are shown on Fig. 14.

All the above readings were taken with the positive pole of the generator connected to the test-plate.

The foregoing experiments indicated that the pressure fall occurred in the immediate neighbourhood of the plate—in fact, at the plate itself, and that when the current was carried to a depth of only 10 ft. the pressure drop in the neighbourhood of the plate was exceedingly small.

Further tests, to make sure of the absence of the possibility of interference, were made by using the pilot wire as the test wire, and taking readings of the difference in pressure between Willesden and an earth-plate in the Brent River about 1 mile from Southall, with the current to earth and without. A varying difference in pressure of from 0·6 to 1 volt was observed when the circuit was worked with a completely insulated system, this being due to the London United Tramways system on the Uxbridge Road. With the current flowing through the earth the readings varied at from 1·6 to 2 volts; thus the effect of the earth current was to raise the pressure by 1 volt.

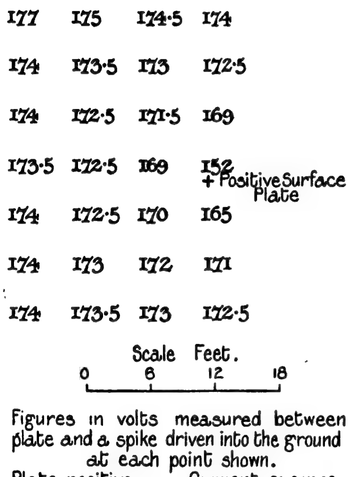


FIG. 14.—Area of Plate.

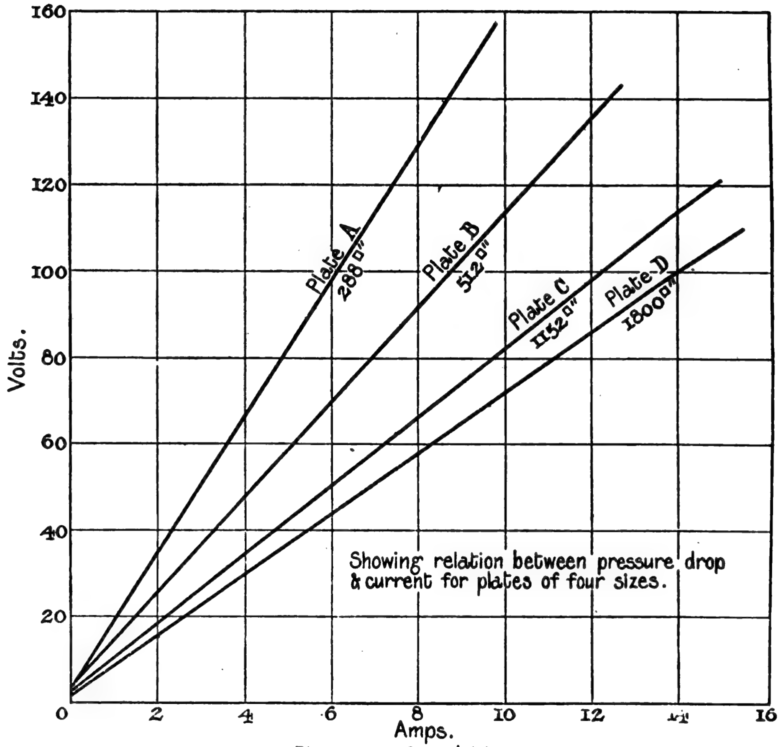
Using the pilot wire connected in parallel with the earth a current of 3 milliamperes was observed without the current in the earth, and 8 milliamperes with 90 amperes flowing, the resistance of the pilot wire being 279 ohms; the difference in pressure between the earth at Southall and Willesden due to the earth current was 1·4 volts.

The latter tests were made by the Post Office engineers, who kindly gave us much assistance in these investigations.

A series of experiments was carried out with different sizes of plates, and Fig. 15 shows the results of the tests on the various sizes of plates used. The tests were made on plates suspended in the canal, and from the results obtained the curves on Fig. 16 were plotted. These curves show that with a current of 1 ampere per 600 sq. in. of plate, little advantage is obtained by making the plate larger.

Further readings were taken, the results of which are plotted on Fig. 17, with similar plates, in order to show the difference between the conductivity of the connection in water and in clay, and also to

show the effect of using three plates situated close together and the same plates situated at various distances apart. The curves indicate that there is little advantage in spacing the plates a greater distance apart than 6 ft. They also indicate that plates buried in clay have more than twice the conductivity of similar plates buried in water. To decide exactly the distance apart at which the plates should be buried a further series of experiments was made, and typical results



Plates in Canal Water.

FIG. 15.

are shown on Figs. 18 and 19. These tests again clearly indicate that when the plates are buried at a distance of 6 ft. practically the maximum conductivity is obtained, and that plates at this distance apart have nearly twice the conductivity of plates 1 ft. apart.

Before completing the above experimental work, earths were made at Willesden and Southall in the following way, namely: At each place three boreholes were made at the positions shown on Figs. 20 and 21, each borehole having a diameter of 7 in. and a depth of approxi-

mately 35 ft. The first series of experiments recited indicated that such a depth was perfectly safe. This gave a current of 33 amperes per plate, and it was considered that the plates could carry this current for temporary use. For permanent use, however, probably six plates would be required so as to reduce the current to one-half. The earth-plates consisted of cast-iron pipes having an outside diameter of 6 in. and a length of 9 ft. To each plate an insulated cable was bonded, and arrangements were made for measuring the current carried by each

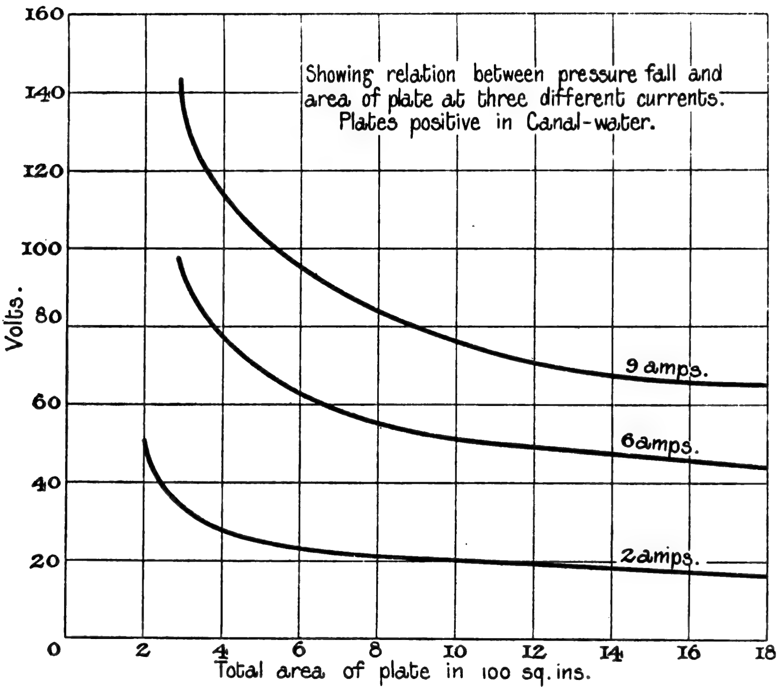


FIG. 16.

plate. After the pipe was placed in the borehole, the space round it was filled in with chalk, the cable being brought up to the surface by means of an insulated tube. The plates at Willesden are all buried in ordinary London clay, and at Southall in fine gravel, which is generally very dry. After the system was started for permanent supply, careful measurements were made in order to ascertain what variations took place in the resistance of the earth connections. The resistance of the two earths is almost exactly 1 ohm, so that although only three plates were used the earth is a very effective one.

It may be said generally that all the experiments show that plates

buried at a considerable depth offer less resistance than plates buried at the surface. I am inclined to think that this is due largely to the heavy pressure on the plate when buried at a depth.

When the earth is put in parallel with either cable, with 90 amperes in the main circuit, 30 amperes flow through the cable and 60 amperes

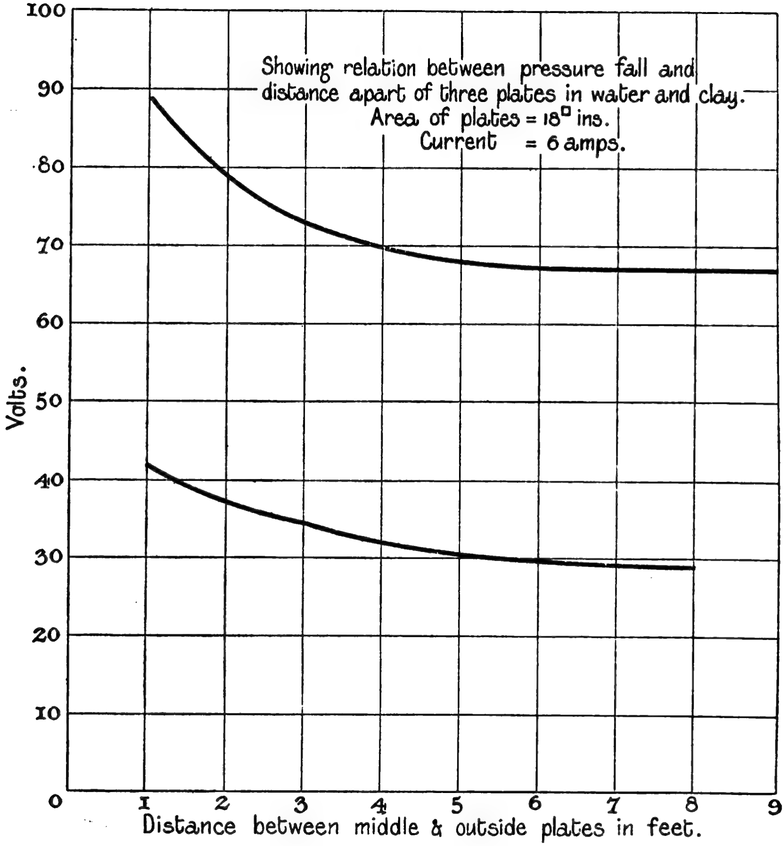


FIG. 17.

through the earth, so that the ordinary resistance of the two earths is approximately one-half the resistance of either cable.

In order to ascertain what change took place in the resistance, a current of 90 amperes was allowed to flow through the earth-plates for some time, and since the figures may be interesting they are given at length, as follows :—

With a constant current of 90 amperes, the Willesden earth being positive, the fall in pressure was as stated below :—

Date, 1911.	Total Fall.	Fall at Willesden.
	Volts.	Volts.
July 13th	108	48
" 14th	108	48
" 15th	94	43
" 17th	100	48
" 19th	94	48
" 19th	99	50
" 20th	99	50
" 21st	100	49
" 22nd...	104	49
" 24th	105	49
" 27th (after rain) ...	75	26
With the Willesden Earth as Negative :—		
July 6th	106	—
" 7th	112	30
" 10th { 10 a.m. ...	118	29
" 10th { 4 p.m. ...	122	
" 11th { 10 a.m. ...	133	28
" 11th { 12 noon ...	137	
" 11th { 4 p.m. ...	143	
" 11th { 9 p.m.* ...	178	
With the Willesden Earth as Positive :—		
July 12th { 10.30 a.m. ...	78	28
July 12th { 5 p.m. ...	94	35
" 13th	108	48

An earth will now be made by driving a shaft 5 ft. in diameter to a depth of 30 ft., and 6 earth-plates consisting of cast-iron pipes 6 in. in diameter, and 3 ft. long will be buried radially at the bottom; in this way it will be possible to keep a close observation of their condition.

The commercial use of the earth as a conductor may be very great. When used as a spare conductor it saves the cost of a spare cable; the cost of the earth connections is a negligible matter as compared with the cost of the cable, and where a very long transmission is required—say, 100 miles—the advantage is immense. A line of 100 miles con-

* This test indicated that the resistance of the Southall earth was rapidly rising, the drop in pressure being at the rate of 10 volts in 20 minutes; at this point the earth connection was broken

sisting of two 0·125 sq. in. conductors will have a total resistance of 68·3 ohms, so that with a current of 100 amperes, the number of kilowatts required to keep the line charged is 683, or nearly 7 per cent. of the maximum capacity of 10,000 k.w. at 100,000 volts. Using an earth return with the same two cables in parallel, and assuming that the earth resistance is 1 ohm (a figure which can be readily obtained) the total resistance would be 18 ohms, and the number of kilowatts to keep the line charged would be 180 k.w. or 1·8 per cent. of the

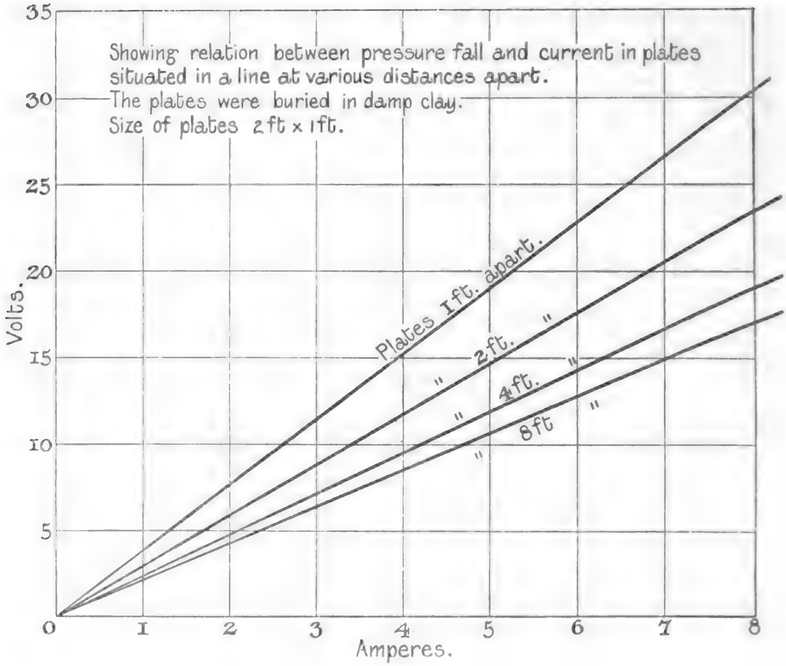


FIG. 18.

total capacity of the line. In the latter case, either conductor would carry the full load of the system so that a complete duplicate transmission system is provided for.

Efficiency.—In my former paper on this subject, I dealt very fully with the question of efficiency; consequently, it is unnecessary to take up much time now. The line loss admits of ready calculation, and I find that the most convenient method is to arrive at the mean power to keep the line charged, to estimate the annual cost of running the necessary plant, and to treat this cost as a standing charge.

I have worked out, and show in the form of curves on Fig. 22 the amount of the line losses at the various load factors, efficiencies

and percentages of the maximum load for which the system is designed. The curves show the value of the losses with a completely

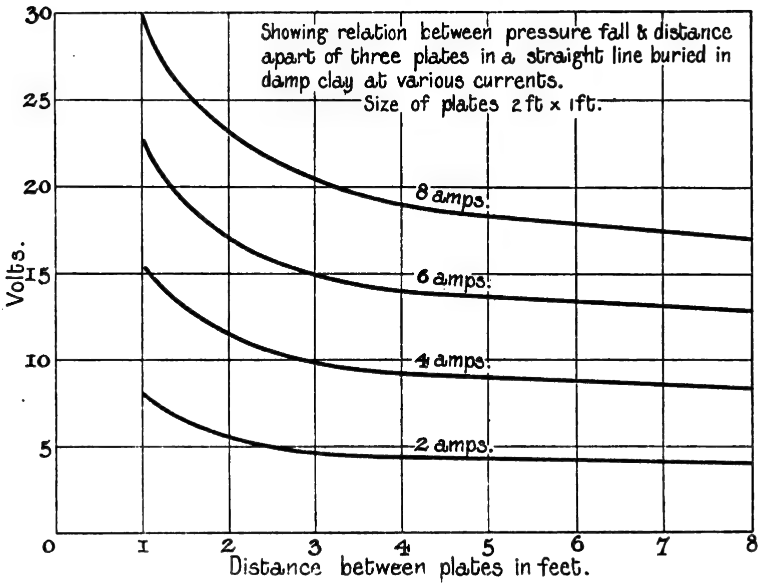


FIG. 19.

insulated system, and for the same system operated with two wires in parallel and with the earth used as the return.

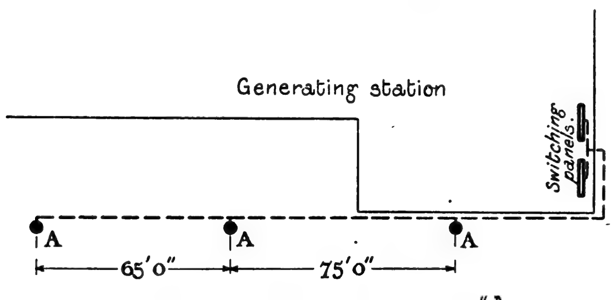


FIG. 20.

The actual working efficiency of the system described is of little value, as the load at present is small—only some 300 k.w. For the last six months the ratio of the 3-phase energy sent out at Southall

to the direct-current input from Willesden was 77 per cent., and during this time the maximum alternate-current load has not exceeded 275 k.w.

Operation.—The actual operating of the plant is exceedingly simple. The first generator is run up to speed by means of its starting motor, either with the mains open or on short circuit, the regulator is set to give the proper line current, an incoming generator is generally started from the direct-current side, and the motor paralleled into the circuit.

The sub-station motors are started by opening the switch and rotating the brushes until full speed is reached, when the regulator

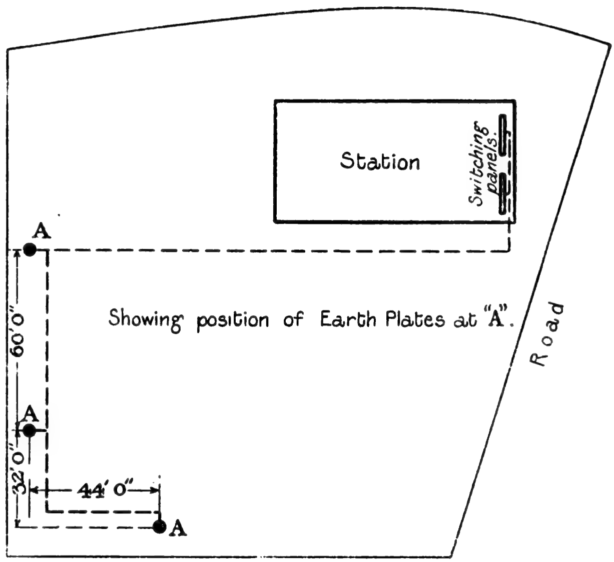


FIG. 21.

is put into action; the speed can be very closely adjusted so that paralleling the sub-generators is a particularly easy operation, one man attending to the plant.

With several generators in series all fully loaded, any failure to one necessitating its removal from the circuit results only in the slowing down of the whole plant.

When two insulated mains are in use, an earth at any point does not interfere with the supply; the voltmeters at once show which main is injured, and it can be cut out of circuit after the system has been earthed at each side of the fault.

When running on one cable with earth return an earth on the cable will cut out all sub-stations beyond the point where the fault occurs.

Size of Generators.—The present safe limit of pressure on a single commutator appears to be about 5,000 volts. Consequently for a maximum line pressure of 50,000 volts, ten machines are required, and if these are driven in pairs, five units of plant are required in the system. The output of each unit depends on the line current adopted; a 300-ampere line would require five units each of 3,000-k.w. output.

It does not seem likely that these high-tension direct-current generators can be built to run at steam turbine speeds, but a turbine drive is now available by the use of the beautiful double helical gear employed by Sir Charles Parsons for driving slow-speed propellers in marine work. A very good plant unit would consist of separate high- and low-pressure turbines each driving by gearing one or two slow-

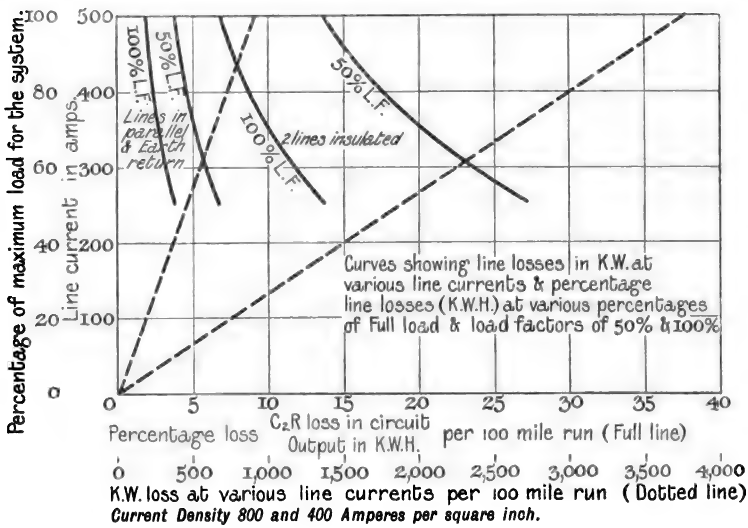


FIG. 22.

speed generators. Careful designing is required for the couplings, but there appear to be no serious difficulties in constructing plant units of very large size.

I am one who believes that the day will come when internal combustion engines of large size will be used to supplement the steam turbine in our power stations, and for such work the series system offers special advantages owing to the fact that it is independent of any ordinary speed variations and is clear of all the difficulties inherent in parallel running.

Cost of the System.—The detailed tables of costs in my previous paper are now in some respects out of date, but the comparative figures are still substantially correct.

The cost of a series direct-current power station where either water turbines, Diesel, gas, or reciprocating steam engines are used is gener-

ally not more than that of a similar alternate-current station. Where large steam turbine stations can be used, direct-current plant of similar output would be more expensive.

The cost of the sub-station plant and gear, as I have already stated, is about the same as that of an alternate-current motor-generator station working at any pressure suitable for direct use on the motors; if step-down transformers are required, the advantage will generally be with the direct-current station.

The transmission line is far less costly than a 3-phase line of similar capacity. The actual cost of the line, having a capacity of 10,000 k.w. with one cable disabled, worked out at £1,600 per mile; this includes the two cables laid in cast-iron pipes and a telephone cable, and the cost of the earth connections at each end. The cost of a single 3-phase armoured cable of 5,000-k.w. capacity at 20,000 volts including cost of laying is about £3,000 per mile or twice the cost without any provision for breakdown.

In many cases I have found the cost of an underground Thury system not to exceed the cost of a 3-phase overhead system of similar capacity.

When I read my former paper on this subject it was inferred by some engineers that I suggested that the series direct-current system would displace the better known parallel systems. This I did not do. I said then, and I repeat, that each has its own sphere, that for certain work the series system and series wound constant-current machines possess great advantages as to cost and convenience over other systems. For very long-distance transmission, especially where underground mains are necessary, it is possible where the alternate-current system is not possible. Where energy has to be taken to a great city from a distance, whether from a water-power station or a steam station situated at the coal-fields, the underground system offers great advantages, as compared with the overhead system, in respect of security of supply and cost of maintenance. In many instances the underground direct-current system can be laid at no greater cost than the 3-phase overhead system. The system might be advantageously used for railway supply, especially where water-power is available, since it enables a very long line to be fed from a single power station. It is nearly as easy and inexpensive to insulate for 100,000 volts as for 20,000 volts; all that is necessary is to design the couplings and machine insulation for the higher pressure. With this high pressure, any practicable distance from a power station is possible.

The series machine is well adapted for any special work where variable speed is required as for driving winding and hauling gear, and for rolling mills. It has been found economical to install a separate series system consisting of a generator and motor, the former driven by a 3-phase motor, to drive a single winding gear. The great advantage for these purposes is, of course, the combination of constant torque with any degree of speed variation and the absence of the losses incurred in any form of rheostatic control.

In conclusion, I am glad to be able to state that the whole of the plant and cables for the western area supply were built in this country. With the invaluable guidance of M. Thury, the company's staff have handled the plant with the greatest success, and I feel it right to bear testimony to their great help in bringing the work to a successful issue.

Discussion.

Mr. Smith.

Mr. ROGER T. SMITH: The author has, on page 872, cited the advantages of the constant torque system with high-tension direct-current transmission for various uses, and has included railways among them. I propose to consider for a few minutes the use of this method purely for railway purposes, it being, of course, clearly understood that the transmission between the generating station and the sub-station alone is referred to, and not the use to which the current may be put on the other side of the sub-station. I think this reservation is necessary because there is a controversy between the advocates of single phase and direct current for railway traction purposes which I do not wish to enter upon. I believe no railway has yet adopted this system of transmission, and it may be useful therefore to see what railway conditions really are. Every railway in general has a strip of land on either side of the permanent way which is in general suitable for high and low-tension transmission by overhead lines on poles. But sometimes the edge of the permanent way comes right up to the boundary of the railway, and we are at once in difficulties with our pole-line and cannot find space enough for it. Also, one or both strips are usually occupied by telephone or telegraph lines, and if for power transmission we are obliged to get rid of these lines by bunching the wires or putting them underground we can only do that at the cost of the power transmission, which will be charged with it. In towns and busy places it is the increasing practice to bunch railway telegraph wires, and either put them into one cable underground, or hang them from carrier wires on poles, or place them above the surface of the ground in wooden troughs. If that practice is extended there should be room overhead for power transmission lines, but it is a rather interesting fact to note how difficult it is on the margin at either side of the permanent way to find room for a line of 3-phase overhead transmission. It is not that the space taken up is the diameter of the pole. The space taken up on the railway is the extreme distance between the two outside wires, plus a certain small margin of safety. If upon one line of poles there are two 3-phase lines, at, say, 20,000 volts between phases, the space taken up would be something like 10 or 12 ft., since it is not safe to put anything below the wires. It is surprising, too, to find in how many places it is impossible to get, for any distance, a space of 10 or 12 ft. with the assurance that it will not ultimately be wanted for traffic purposes, such as widening of the line. As an alternative to a transmission of, say, 100 miles—the figure taken by the author—a 3-core cable for transmitting alternating current may, of course, be put in duplicate underground. If such cables are to be laid in such a way

Mr. Smith. that they are not going to be damaged by the permanent way department the cost is very considerable, and the author's proposal to use two high-tension direct-current cables is in general a cheaper alternative. The system may be most useful for railway purposes, and should always be considered. If, in addition, it is possible to use the earth as a return there is a still greater advantage on the side of direct-current high-tension transmission cables. With regard to the earth return I wish to ask one question. Track circuiting for signalling is increasing on British railways, and engineers, to an increasing extent, are putting in alternating current for track circuiting in busy places, or where there is likely to be interference by electric tramway or other stray currents, but in places which are not busy, and where there is no expectation of stray currents, it is quite extravagant to use anything else but direct current for track circuiting by means of primary or secondary batteries at 2 or 4 volts, and such systems are obliged to use the earth. I would ask the author if he could give any assurance that such small voltages as these are not likely to be interfered with by such earth returns as he has put forward. If, then, there is not going to be any interference with track circuiting, because I think interference with telegraphs and telephones is not so vital, I am sure that for any scheme of railway long-distance transmission this system ought to be carefully gone into and considered, because underground or overhead cables could be cheaply laid down upon the boundary of the railway property. Of course the system implies rotating machinery in the sub-station, where such machines may be used to supply direct or alternating current for traction or otherwise. I would also ask if the author has considered the use in sub-stations of machinery for charging low-tension batteries in parallel or the charging of batteries in series direct from the line. For all traction purposes, except for suburban service, loads are very intermittent, and it may be necessary to use batteries for storage.

Dr. Rosenberg. Dr. E. Rosenberg: The author has given us a very interesting paper which in a fair way explains the advantages of the high-tension direct-current transmission without claiming advantages which it does not possess. The one thing that is clearly proved is that the transmission line is very much simpler and very much cheaper with direct current than with alternating current. Where the transmission line is an all-important factor, the merits of the high-tension direct-current system will therefore be great. Also the switchgear is simple and cheap. On the other hand, the generation and transformation of the direct-current is more complicated and costly and less reliable than that of alternating-current, and the motors have not the beautiful self-regulating qualities of an alternating-current induction motor or of a constant-voltage direct-current shunt motor, and therefore require an outside mechanical regulator. The author dwells upon the difficulties of alternating-current plant running in parallel. There are, of course, cases on record where difficulties have been experienced in parallel running, but for one trouble case there are at least 9,999 of smooth running, and furthermore, if the matter is studied beforehand, we can, nearly with certainty,

Dr. Rosenberg.

guard against difficulties. One advantage of alternating-current plant running in parallel is that the engines are positively kept in step and that no matter whether the governor is acting or not the engine cannot change its speed as long as its alternator is coupled to the supply. This is not the case with a direct-current series system. On page 854 the author says that arrangements have been made to vary the current of the system in question from 70 to 120 amperes. In such a case it would not seem possible to work always with full steam or water admission in the engine or turbine driving the generator. Therefore here we must be dependent upon the governor of the engine. If the generator is driven by a motor the set must be protected against running away in case of the motor supply failing. This difficulty does not exist in alternating-current stations. Even alternating-current systems of different frequency do not by any means represent great difficulties for interlinking. Motor-generator sets can be used either with slip-ring motors or self-starting synchronous motors provided with amortisseurs, and there is no difficulty in the way of putting in parallel to such a set any engine-driven alternator in the sub-station, provided it is possible to change within certain limits the speed of this engine. I could show several cases of successfully interlinked alternating-current stations of different frequencies. In any case, however, the different frequencies are not the rule, and where we have the same frequency an alternating-current sub-station consists only of static transformers, which are our most reliable apparatus and require no attention whatever. In such cases, of course, the costs of the sub-station are also far lower than those of sub-stations with rotating machinery. The chapter describing the experiments with earth-plates is of the greatest interest, and most instructive. The author's observation that the earth-plates showed no wear whilst, theoretically speaking, they should have been oxidised away in less than two months, reminds me of experiments with aluminium cells used as electrolytic valves between a direct-current dynamo and an accumulator battery. Here also no wear of the aluminium electrodes takes place, although the current flows continually in the same direction. On page 859 the author mentions that a resistance of 0·8 megohm is fitted to the machine frame, the ends being connected to the terminals and the centre point to the frame of the machine in order to limit the pressure between either pole and the frame to half. I believe that this arrangement would achieve its aim only during normal working, but should the insulation between one terminal and frame break down, then this resistance could not prevent the other pole from obtaining full potential to earth. The direct-current series system has very great advantages in the transmission, but also very serious disadvantages in the generation, transformation, and direct use of the current. These remarks are not meant by any means in a disparaging way, as no one is more willing than I to express the greatest admiration for M. Thury, the father of the direct-current series system, and for the wonderful results which he has achieved in spite of numerous difficulties.

Professor Marchant.

Professor E. W. MARCHANT: I only want to refer to one point which has not been mentioned in the paper, and that is the possibility, when the earth is used for a return, that corrosion may take place. I am not, of course, suggesting that in the case the author is dealing with there was any serious corrosion, because, as I understand the system, the earth is only used as a return in case of a breakdown; but the paper also discusses the commercial possibilities of the earth as a return, and the earth is considered as a possible permanent return for current. The corrosion which may occur in pipes which have been already laid is a very serious matter. In this connection I want particularly to refer to the effect of the character of the soil upon the amount of chemical action and corrosion. In Liverpool not very long ago we had a very interesting example of chemical action in soil containing a very small percentage of potash and soda. The particular case was that of a cable laid in a trough in bitumen—it was the negative of a 3-wire main. The bitumen cracked, and the action of the current produced potash and soda in a mass of about half a hundredweight round this fault. On analysis it was found that this mass consisted almost entirely of caustic potash and caustic soda with pure potassium and sodium nodules. That occurred in a soil in which, as I have said, the percentage of potash and soda was extremely small, and the material which had collected had been gathered from a very large volume. I imagine that that is not likely to be a serious drawback in the case of the system described, because, if the earth return was the negative, and if such action occurred, it would be where the plates could be easily renewed. A much more serious matter is the possibility of chemical action in conductors which serve to convey the current back to the station, but which do not appear to form part of the return, such, for example, as water pipes. The other subject to which I should like to refer is the machine which has been used in connection with the high-tension direct-current tests on the cables. Mr. Watson was working in my laboratory for about eighteen months, and built a small machine of the same type as that used in the test. I think it is no mean achievement to have developed this machine, as he has done, from a machine with an output of a few watts to one with an output of half a kilowatt.

Mr. Wigham.

Mr. J. C. WIGHAM: It is interesting that the author should have brought this paper before us here, because, as the Lord Provost pointed out, Glasgow had often thought that it ought to be supplied by water-power. Now the difficulty is that waterfalls such as the Falls of Clyde are individually not large enough to be of any real value, but in the Highlands of Scotland there are many falls which could be made available, on a very reasonable capital expenditure, to give two, three, or five thousand horse-power, and by this system of transmission it would be possible to yoke these powers together and make them available for use in Glasgow. With regard to the reliability of high-tension plant, I have had superintendence of high-tension direct-current machinery for some twelve years, and our experience of the transformers is that they are no more

troublesome to handle than ordinary low-tension direct-current machinery. The commutators have given no trouble and we have not more breakdowns than with low-tension machinery. In fact as many of the breakdowns have occurred on the low-tension side of the transformers as on the high-tension side. In one of our high-tension direct-current transmissions we are arranging to construct earth connections under the advice of the author on the system described in this paper, but unfortunately it has not been possible to carry out the test in time to give the results to the meeting. Mr. Wigham.

Mr. C. CUTHBERTSON: With regard to the regulator which the author uses upon his machines, I think it would no doubt be interesting to many if he would tell us in what way the power taken by the regulator affects the efficiency of the machines. Upon the question of the reliability of the high-tension direct-current machines, I have recollections of a number of breakdowns of similar machines on two different "Oxford" systems some years ago, and I would like to ask the author whether he considers that machines of this particular type are more liable to break down than those with which he has compared them. Mr. Cuthbertson.

Mr. B. WELBOURN: Five years ago, a short time after the author read his first paper upon this system, I had the advantage of visiting Canada and the United States, and was very much impressed by the interest created among transmission engineers by the reading of that paper. In Canada there was one large scheme under consideration where the system was seriously considered for use, and I formed the decided opinion that if the proposals put before the engineers had been followed up in person by one like M. Thury or the author, who knew the system, it would have run a fair chance of adoption. The difficulty, of course, which lies before any designer of a big power transmission system who proposes to deal with it on the direct-current method, is to determine what the load is likely to be for some years to come and then to decide what the current should be, as well as the voltage. In those cases where this can be done with fair accuracy I think there is a great field for direct-current for point-to-point or railway supply, with of course the reservation made by Mr. Roger Smith. The introduction of this system into England marks the beginning of an entirely new phase of engineering. It is also causing an immense amount of research work on the part of many manufacturers, particularly cablemakers, and has increased our knowledge of the properties of impregnated paper insulation not only for direct-current but also for alternating-current work. On page 852 the author mentions the alternating current pressures to which the cables were subjected in the factory. I would like to supplement that by saying that on the last length of cable tested, after the conclusion of the 5 minutes' test at 130,000 volts alternating current, the pressure was raised at once to 150,000 volts, which was the highest pressure available at the time in the works, and was maintained for 3 minutes without failure. As to joints, no joint should be submitted for approval which will not pass a test of 100,000 volts alternating current for 1 hour; 150,000 volts alternating current was the pressure Mr. Welbourn.

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to which sample joints were subjected immediately after being subjected to 100,000 volts for an hour. The test was therefore very severe and affords a sound basis for the contractors' confidence in their work. I was particularly interested in the tests on earthing. They agree almost *in toto* with a test made elsewhere to determine the distribution of the plates. So far as we are concerned it might be thought that cable-makers would be frightened at the commercial use of earth, but my attitude towards it is exactly this: that everything that can be done to extend the use of electricity is to the advantage of the manufacturers as well as of the community. Although it does not directly arise from the paper, I would ask the author whether he can tell us what precautions were taken for protection against lightning troubles on the Moutier-Lyons overhead line. I would like to conclude my remarks by thanking the author for the opportunity he has given English manufacturers of showing what they can do in turning out plant of a reliable character for dealing with high-tension direct-current work at 100,000 volts.

Professor Baily.

Professor F. G. BAILY: From some experiments I have made on earth currents I am inclined to think that the return current proposed in the paper would not be a serious matter except in the immediate neighbourhood of the plates, and if these are deeply buried the surface, even in the vicinity, will be little affected. Owing to the spreading of the current in all directions the current density becomes extremely small, and probably a total current of 100 amperes would spread to such an attenuation as to become comparable to the irregular currents that are usually flowing about the earth. The risk of electrolysis of iron pipes in the intervening country is remote, for the conductivity of an iron pipe is negligibly small compared to that of the vast path through the ordinary strata, and the proportion of current it will convey will be correspondingly minute. For the same reason I feel almost confident that railway signalling will not be sensibly influenced. A different problem is, however, raised in the immediate neighbourhood of the positive plate. With a direct current it is well known that electric endosmose takes place when a gradient of potential exists in a moist porous solid. The effect is proportional to the potential gradient, and if the ground near the plate is rather dry the gradient will be fairly large, and moisture will be removed from this neighbourhood. This will increase the action and the voltage will rapidly rise, for the 100 amperes has the immense voltage of the station at its back and is bound to flow through, whatever the resistance. There will be some considerable heating, and though this will lower the resistance and tend to limit the rise of voltage, it will be wasteful. Moreover, under these extreme conditions the surrounding surface of the ground might not be entirely safe. One of the tests given in the paper seems to indicate that this phenomenon was beginning. The voltage rose steadily until the voltmeter was taken out of the circuit. Fortunately this phenomenon gets a start only when the ground is fairly dry. If it is moist the potential gradient will not be enough to overcome the

natural diffusion of moisture back again, so that the author will only require to bury his plate near an underground spring or in a water-bearing stratum, and in the neighbourhood of Willesden these conditions should not be difficult to satisfy. Professor Baily.

Mr. W. McWhirter: I should like to refer to the very interesting remarks of the author upon earthing. Many years ago I remember in connection with railway train signalling in the English Lake district, near Coniston, we had great difficulty in working owing to the currents meant for one station passing on to the next station and affecting the signals there. An examination of the earthing arrangements showed it to be made up of a wire to the metal body of a pump and a further connection to the railway metals to which a galvanised iron wire was carefully bonded, yet on testing the earth resistance was found to exceed 150 ohms. In a field opposite the railway station where the soil was quite wet we opened up two trenches to a depth of 5 ft. and put in large coils of wire surrounded by coke, and after filling in the soil these were joined up to the other earth connections, and on again testing we found the resistance reduced by only a few ohms. A river flowed underneath the railway about 100 yards distant, and we lowered several large coils of wire into the river-bed and connected to our earthed system, and even then the resistance exceeded 100 ohms, and signals were still affected by stray currents. A further examination of the pump showed that a leather washer had been inserted between the pump body and the suction pipe, and when the earth wire was joined direct to the suction pipe the fault was completely removed and the earth resistance fell to only a few ohms. Similar difficulties have often arisen in providing earths for lightning conductors, and damage has often been caused clearly due to faulty earths. On one occasion, testing the earths on a magazine near the sea, these were found practically non-existent, and it was demanded that each earth resistance should not exceed 2 ohms. Four complete lightning conductors were erected on the magazine, and new earth-plates of copper, each about 20 superficial feet (measuring both sides) were fitted and sunk in trenches 12 to 15 ft. deep in sand permanently wet, nevertheless, the resistance was so high that we had to connect all the plates and conductors in parallel by means of heavy copper tape, and even then the earth resistance of the four plates exceeded 20 ohms. In the first example I believe the trouble was due to all our earths being placed in a pocket of rock which was practically insulated from the surrounding country, and in the second the conductivity of the soil, or rather sand, was very low, but no doubt the earths might have been improved by sinking the plates probably twice as deep to get them below high-water level. In the vicinity of London, where there is a huge reservoir of chalk saturated with water, extending to many miles in area, it might be easy enough to find excellent earth connections as shown by the author, but in the Lake district in England and the Highlands of Scotland I am sure that owing to local conditions earthing would be an exceedingly difficult and expensive matter. Mr. McWhirter.

Dr. Ferranti.

Dr. S. Z. DE FERRANTI: I recall an experience some twenty-two years ago when a failure took place in the lead-covered cables that supplied current to London from Deptford which was just being started, and we were forced on a great emergency to send about 1,000 k.w. through a single cable, using the earth as a return. This resulted in a loss in the earth return of about 1,500 volts. It will be seen how different it was then with alternating current to what the author has now done with continuous current. Apart from the loss of energy involved there was in the case I refer to a hopeless state of affairs set up in all telephone and telegraph circuits. In fact, it is not too much to say that all the traffic round London was brought to a standstill. Not only was the telephone and telegraph service paralysed in the London area, but telegraphing as far as Rome was seriously interfered with. Fortunately for us the cause of the mishap was given out later as the result of a remarkable electric storm! It is highly probable that in the near future continuous-current earth returns will play a large part in the saving of money, and developments will be looked forward to with interest.

Mr. Highfield.

Mr. J. S. HIGHFIELD (*in reply*): I am particularly interested in Mr. Roger Smith's remarks on the possible use of the series system for transmitting energy to railway sub-stations. Where the high-tension lines can be carried overhead, the space occupied by a series line is very much less than that occupied by a 3-phase line. I consider that in most important railway transmission schemes the high-tension lines will be laid underground, partly for the reason given by Mr. Roger Smith that there is not often sufficient space for the overhead lines, but chiefly because the risk of damage to the overhead lines is rather great, whereas, with underground cables laid on each side of the track, so far as the transmission line is concerned almost absolute security from interruption can be attained. The charging of batteries is, of course, quite possible on a series line, although special precaution is necessary to insulate the batteries owing to the high tension employed. Where direct current is used for working the trains, however, it is much the best plan to couple the batteries in parallel on the low-tension busbars; in this way the battery losses are greatly reduced, and the operation is rendered much more easy.

Mr. Roger Smith, Professor Marchant, Professor Baily, and other speakers, have raised many interesting points in relation to the use of the earth as a permanent conductor. There is no doubt whatever that the value of the earth as a conductor is very great. By its use the capital cost of a transmission line can be greatly reduced and the efficiency improved. The difficulties are to make the connection to earth in such a way that no interference will be caused to signalling, telephones, and similar circuits, and to ensure that the earth connection shall be reasonably permanent. By making the connection at a considerable depth below the surface, the first difficulty can be overcome. The depth below the surface depends a great deal on the nature of the surrounding soil. It is not possible to make the con-

Mr. Highfield.

nection to hard rock, and where a rock stratum is covered by a comparatively shallow depth of clay or gravel, it may become necessary to get through the rock. If the current density be kept low, there appears to be very little action on the earth-plates, but my experiments on this subject are really not complete, as they of necessity take a very long time. I am quite satisfied, however, that at moderate expense a satisfactory earth can be made in any district except where hard rock exists.

Mr. McWhirter's experiences with earth connections well illustrate the difficulties that arise and the sort of troubles that have to be looked for when endeavouring to make a satisfactory earth connection.

Dr. Rosenberg, in his opening remarks, brings out the points in favour of direct-current transmission. His remarks about generation and transformation are perfectly correct when steam turbine-driven generators are used, and when static transformers are compared with direct-current motor-generators, but, so far as my experience goes, high-tension direct-current motor-generators are in every way as reliable as either alternating-current motor-generators or rotary converters. The arrangement of the sub-station is very simple, and the operation of the machinery calls for less expert attention. Regarding the governing of the power station plant, there is no more difficulty with the direct-current series system than with any parallel system, and under certain conditions engine governing is not required. Where the generators are driven by water turbines, if the machines run at fairly constant loads, the simplest method of governing is to vary the speed of the turbines by means of an automatic governor controlling all the turbines. So far there is no case where series machines are being driven by steam turbines with gearing. In such cases probably it would be best to use the ordinary constant-speed governor for the turbine and to maintain the current constant by rocking the brushes with the ordinary type of regulator. Where the series machines are driven by reciprocating steam engines, no governor is required except a runaway governor, since both the series machine and the steam engine, working on a fixed cut-off, are constant torque machines. It follows that if the cut-off is fixed, the current given by the series machine will also be fixed, and the speed of the machine would depend on the resistance of the outside circuit, that is to say, on the pressure called for from the generator in order to maintain the current in the outside circuit constant, the value of the current to be altered by altering the point of cut-off. The steam engine, under these circumstances, would work with varying rates of speed to suit the load on the generator.

Dr. Rosenberg's remarks on the parallel running of two or more alternating systems of different frequency are most interesting. The problem is, I think, a peculiarly fascinating one. I do not, however, quite agree with Dr. Rosenberg that the difficulties are slight. I believe he would be the first to admit that, under certain conditions, the difficulties of successful parallel running would be very great; for

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instance, where it was desired to exchange a small amount of power from one large station to another station of moderate size. There can, I think, be no question that the linking together of several power stations of different frequencies can be done in a more simple way by means of direct-current transmission than by alternating-current transmission. Of course this can, at best, be considered as a broad statement only, as probably each case would have to be considered separately; there are so many variables in such cases that it is impossible to make any general rules, and I should be the last to suggest doing so. I do not wholly agree with Dr. Rosenberg when he refers to the serious disadvantages in the generation, transformation, and direct use of the current. These depend entirely on circumstances. Where the steam turbine is the most suitable drive, then the series generator must be driven by means of gearing, and the alternator is, therefore, clearly the most suitable machine for the purpose. Similarly, with transformation, where the static transformer is the most suitable device because alternating current is to be used directly, then the direct-current plant is not only more expensive to instal but more expensive to operate. Where, however, the prime movers are driven by gas or oil, or are reciprocating steam engines, there is really nothing to choose between the two systems. Again, in connection with water turbines, generally there is little to choose, although where very large power turbines are employed the alternator is the most convenient machine. Regarding the direct use of power, there are many cases where the constant-current series machine is incomparably more suitable than either the alternating-current machine or the ordinary constant-pressure direct-current machine. For driving any load where the speed is constantly varying over wide limits, for winding engines or rolling mills, the constant-current series machine provides, in most cases, far and away the best solution. In many of these cases, where an alternating-current supply is available, I think the best method is to use such supply for working a small local series system to supply constant current to these variable loads. The employment of a flywheel for storing the energy is particularly easy with this system, and one flywheel machine can be used to balance the supply to a number of motors. This subject is rather too long to deal with in a reply, and I must defer its elaboration for some future time.

It is satisfactory to hear from Mr. Wigham that he has had so little trouble with the direct-current high-tension machinery which has been under his control for many years. There is no doubt, as Mr. Wigham says, that where a number of water-power stations are available they can be most conveniently linked together on the series system.

I cannot give Mr. Cuthbertson the exact power taken by the regulators, but they are driven by a 2-in. leather belt, so I imagine that the power taken does not exceed $\frac{1}{2}$ H.P. Mr. Cuthbertson refers to breakdowns on parallel-worked machines on the "Oxford" system. These machines, I take it, are similar to those with which Mr. Wigham has had so little trouble. There have been immense improvements in the

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methods of building these machines, but apart from that it is clear that a machine carefully insulated from earth—as are all the generators and motors on the series system—must have a much larger factor of safety so far as breakdowns to earth are concerned than a machine working with a grounded frame.

Mr. Welbourn is quite right: research work carried out with one object very often results in great improvements in unexpected directions. It is interesting to note that the work that has been done has enabled satisfactory commutation to be obtained with pressures up to and exceeding 5,000 volts on a single commutator. This work has directed the way in which to design direct-current parallel motors for working pressures in excess of anything that appeared likely three or four years ago. Quite apart from the series system, this increase in the working pressure of direct-current machinery will, I am convinced, in the future lead to very great developments.

I particularly regret that M. Thury was not able to be present with us to-day, as I am sure we should have been interested to have heard him on this subject upon which he has worked for so many years.

OBITUARY NOTICES.

OVIDE F. DOMON was born in 1861, and received his education at Geneva. In 1880 he worked with Messrs. Siemens at Paris, and for a time was also assisting the Edison firm in the same city. From 1884 he assisted the Oerlikon Company, becoming in 1895 chief of the electrical department. In 1897 he went to Lourenço Marques to superintend the erection and running of lighting plant. On his return to London he became resident consulting engineer to the Oerlikon Company in 1900. In 1903 he went to Kuala Lumpur, in the Malay States, and was there at the time of his death in August, 1911. He was elected a Member of the Institution in 1903, and was also a member of the Swiss Association of Electrical Engineers.

MAJOR-GENERAL EDWARD ROBERT FESTING, C.B., was born in 1839, and was educated at Carshalton and Woolwich. He became at the age of 17 a lieutenant in the Royal Engineers, and in that capacity he served in Central India from 1857 to 1859. In 1864 he was appointed deputy general superintendent of the South Kensington Museum, becoming in 1893 director of the Museum, and retiring in 1904. He had a remarkable power of mental calculation, and he wrote several valuable papers for the Royal Society, of which he was elected a Fellow in 1886. He was elected a Member of the Institution in 1888. He died on 16th May, 1912.

JOHN CRISP FULLER was born at Bristol in 1821, where he spent his early days, and on coming to London about 1850 he became interested in the electric telegraph. In 1854 he obtained a position with the Electric and International Telegraph Company, where he worked in company with Faraday and other well-known pioneers. He devoted his attention specially to batteries, and was the inventor of the mercury bichromate battery, and the Common Battery system of telephone working. In 1857 he assisted Messrs. Silver & Co., of Silvertown, in the designing of vulcanite insulators, and afterwards assisted Mr. W. T. Henley in the manufacture of submarine cables. In 1868 he went into business as a telegraph engineer at Old Ford, and continued there to the time of his death, which occurred on 26th October, 1911, when he was over 90 years of age. He had been a member of the Institution since 1875.

HENRY LEA was born at Birmingham in 1839, was educated at King Edward's School, and received his first training as a mechanical engineer under Mr. J. E. Hodgkin and Messrs. May and Mountain, of Birmingham. He afterwards spent some time in the works of Mr. Walter Williams, where he acquired a knowledge of rolling-mill practice and bridge construction. In 1860 he was elected a member of the Institution of Mechanical Engineers, and two years later he began practice as a consulting engineer. His practice for twenty years was that of a mechanical engineer, but in course of time he took up various electrical matters, and in 1882 he definitely added all classes of electrical work to his former practice. In the same year he carried out the lighting of Birmingham Town Hall by means of glow lamps, replacing the former installation of "Jablochkoff candles." This was at the time the largest installation of glow lamps that had ever been carried out; the power was obtained from a rolling-mill engine at the Winfield Works, through countershafts, and the transmission was by underground mains in iron pipes. Mr. Lea was also associated with Colonel R. E. Crompton and Lord Justice (then Mr.) Fletcher Moulton in drafting the first electric lighting order, that for Chelsea. He was responsible for a large number of lighting and power installations, including the lighting of the Birmingham Technical School and the Birmingham University, and an electric fan installation at the Birmingham General Hospital. He served on the Engineering Standards Committee as a representative of the Institution of Mechanical Engineers, and was twice Member of Council of that Institution. He was elected an Associate Member of the Institution of Electrical Engineers in 1884, and was transferred to full membership in 1893, being also Chairman of the Birmingham Local Section for the session 1902–3. Mr. Lea was possessed of great mechanical skill, and in his spare time constructed models of railways and locomotives, many of which were shown at exhibitions. He died on 20th July, 1912, at the age of 73.

WILLIAM CRAMMOND MARTIN was a native of Dundee, and at the age of 17 entered the service of the National Telephone Company. He was afterwards with the Brush Company of Scotland, and in 1883 went to Glasgow, and was with Messrs. Andrews & Co., Messrs. Mavor and Coulson, and Messrs. Paterson and Cooper. In 1893 he commenced business on his own account, and his firm carried out a large amount of installation work on ships for lighting and power purposes. The firm obtained in one year electrical contracts for over thirty steamers, including the liner *Mauretania*, on which over 6,000 lights were installed, and 200 motors for various power purposes. Mr. Martin was Chairman of the Scottish Section of the Electrical Contractors' Association, and served on the Glasgow Town Council. His death took place on 29th October, 1911. He was elected an Associate in 1893, and became an Associate Member in 1902, and a full Member in 1909.

WILLIAM GEORGE MEDDINGS joined the New Zealand Telegraph Service in 1856, and held the position of Inspector of Telegraphs at Christchurch for nearly forty years. In 1900 he went to take up similar duties at Nelson, and in 1903 at Auckland. He retired from the service in 1909. He was elected a Member of the Institution in 1878. His death took place on 1st November, 1911.

ERNEST MERCADIER died on 27th July, 1911, at the age of 76. He entered the French Telegraph Service about 1859, and was Director of Telegraphs at the siege of Paris. After the war he became Professor of Physics at the Ecole Supérieure de Télégraphie, Paris, and in 1881 Director of Studies at the Ecole Polytechnique, which post he held until 1903. He was the inventor of the multiple telegraph, and wrote some books on telegraphy. He was elected a Foreign Member of the Institution in 1881, and in 1911 was transferred to full Membership.

EDGAR W. MIX, who died on 12th November, 1911, was educated at Columbus University, Ohio, where he graduated in 1888, and soon afterwards entered the service of the Thomson Houston Company at Lynn, Mass., and was specially entrusted with the development of the Thomson recording wattmeter, which under his supervision took first prize in the meter contest at Paris in 1890. He afterwards remained at Paris with the Thomson Houston Company, where he did a considerable amount of tramway and alternating-current work. He was elected a Foreign Member of the Institution in 1895, and was transferred to full membership in 1911.

ANTONIO PACINOTTI was born on 17th June, 1841. At Pisa he attended the Laboratory of Applied Physics, where his father, Luigi Pacinotti, was Professor. At this time (1858) his attention was directed to a special type of electromagnet, termed by him a "transversal magnet," now generally known as a ring electromagnet. His experiments on this form of magnet may undoubtedly be set down as marking the first phase of his advance which led eventually to his continuous-current dynamo. However, Pacinotti's experiments were destined to be interrupted, for in May, 1859, he had to leave Pisa, in order to serve in the Garibaldian wars, where he was sergeant in the Tuscan division of the engineers. During this strenuous time Pacinotti was still pondering over the problem of how to increase the induction of his cores (or, as it would now be looked at, seeking to reduce the magnetic reluctance of the circuit); and the toothed ring armature was the result, so that the invention may be said to have originated on the battlefield.

On his return to Pisa in 1860, Pacinotti went on with the construction of his machine, with the single continuous ring winding, which then assumed definite shape. His experiments with this machine are fully described in the memorable issue of "Il Nuovo Cimento" of 3rd May, 1865. The later work of Pacinotti resulted in the invention of several different forms of dynamos, but at the same time he continued his regular work of teaching physics at the University of Cagliari, and

later at Pisa, where he was appointed Professor, after the death of his father. An examination of Pacinotti's published researches and the sketches therein, shows that even at that time, when the general conceptions regarding electrodynamics and magnetism were so uncertain and obscure, he had, with unerring genius, obtained a very clear grasp of the phenomena concerned. Thus we find that as a result of his early investigations on ring magnets, he proposed a system for the transmission of angular movements, by leading in the current into different portions of the ring. A very few steps further in this would probably have brought him up against the problem of the rotating magnetic field, which later on was so ably demonstrated and applied by his fellow-countryman, Ferraris.

Professor Pacinotti was elected an Honorary Member of the Institution in 1902. He was awarded the Order of the Crown of Italy, the Order of Merit of the House of Savoy, was a Chevalier of the Legion of Honour, and the recipient of numerous other distinctions. He died on 25th March, 1912.

BENNETT PELL was born on 16th August, 1842, near Canterbury, and received his professional training at the London station of the Submarine Telegraph Company, where he began work in 1857. On the laying of the first cable to Germany he was transferred to the Continental station at Emden. In 1860 he joined the United Kingdom Telegraph Company, and although only 18 years of age was placed in charge of their Birmingham station. At the age of 21 he became connected with the Indo-European Telegraph Department, and occupied important positions at home and in Persia and the Colonies until 1874, when he was appointed general manager of the Eastern Extension Australasia and China Telegraph Company at Singapore. Here he established the first telephone exchange in the East, which was afterwards purchased by the Oriental Telephone Company. In 1882 Mr. Pell returned to England and took up work with Messrs. Johnson and Phillips, where he brought out the Brockie-Pell arc lamp, and formed a separate company to acquire the rights of manufacture of this lamp. He retired from the electrical profession in 1898. He was elected a Member of the Institution in 1875, and was also a Fellow of the Imperial Institute, and a member of the London Chamber of Commerce. His death occurred at Exmouth on 20th September, 1912.

EDOUARD RAU was for thirty-five years a well-known civil engineer at Brussels, and invented various devices in connection with railway signalling and telegraphs, and previous to joining the Institution in 1877 had written a book on telegraphy and one on electric fire-alarms. He died on 7th February, 1912.

WILLIAM EDWARD ROBSON was born in 1874 and received his electrical training in the works of Messrs. E. Scott and Mountain,

of Gateshead. He was afterwards designer to Messrs. Armstrong, Whitworth & Co., the Brush Electrical Engineering Company, Loughborough, and the British Electric Plant Company, Alloa, and also conducted evening classes in electrical engineering under the Durham and Fife County Councils. Under Messrs. Armstrong, Whitworth & Co. he designed the first application of electric power to gun and turret training on warships, and at Alloa he designed some of the earliest power systems for the driving of printing presses, factories, and collieries. In 1906 he was appointed lecturer on machines and design at the City and Guilds Central Technical College, which position he held at the time of his death on 15th August, 1912. He was elected a Member of the Institution in 1911.

LOUIS JAMES BERNARD WALL was born in Australia in 1870, and at the age of 26 entered into partnership with Mr. W. J. Splatt at Perth, West Australia, where from a very small beginning they built up a very extensive business. Latterly the firm had been taking an active part in the development of the collieries of the neighbourhood. His death occurred after an operation on 6th April, 1912. He was elected a Member of the Institution in 1900.

WILLIAM RYLE WRIGHT was born in 1876 and educated at Owen's College, Manchester. In 1891 he was with the Electric Construction Company, and afterwards became electrical assistant successively to the Corporations of Manchester, Burnley, Bootle, and Wellington (New Zealand), at which last town he designed and constructed the tramways. In 1905 he installed electric plant at the Allandale Colliery, Dunedin, and in 1906 he was resident engineer during the construction of the tramways at Shanghai. After this he returned to England and carried on private practice as a consulting engineer in London. His death occurred in January, 1912. He was elected a Member of the Institution in 1909.

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EXPLANATION OF ABBREVIATIONS.

(P) indicates a reference to the author and title of a Paper.

(D) indicates a reference to remarks made in a Discussion upon a Paper, the title of which is quoted.

Note.—The lists of speakers in the Discussion upon any Paper will be found in the Table of Contents at the beginning of the volume.

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